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Sustainable High-rises

Design Strategies for Energy-efficient and Comfortable Tall Office Buildings in Various Climates

Babak Raji

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Contents

3 Early-stage design strategies 83

TOC

List of Tables

List of Figures

TOC

TOC

TOC

TOC

Summary

With the aim to limit the number of ineffective designs, this dissertation has investigated the impact of architectural design strategies on improving the energy performance of and thermal comfort in high-rise office buildings in temperate, sub-tropical and tropical climates. As the starting-point of this research, a comparative study between twelve high-rise office buildings in three climate groups was conducted. For each climate group, three sustainable high-rises were selected and one typical high-rise design as a reference. The effectiveness of architectural design strategies was compared between the two categories of buildings (high-performance versus low-performance) concerning their potential impact on heating, cooling, lighting and ventilation loads. Certain architectural design strategies were found to be major determinants of energy performance in high-rise buildings. These can be classified under the categories of geometric factors, envelope strategies, natural ventilation strategies, and greenery systems. To quantify the extent to which these architectural design strategies affect energy use and thermal comfort of tall office buildings, simulation studies were carried out.

To quantify the impact of geometric factors on the energy efficiency of high-rise office buildings, performance-based simulations were carried out for 12 plan shapes, 7 plan depths, 4 building orientations and discrete values for the window-to-wall ratio (WWR). The results of the total annual energy consumption (and different energy end-uses) were used to define the most and least efficient solutions. The optimal design solution is the one that minimises, on an annual basis, the sum of the energy use for heating, cooling, electric lighting and fans. The percentile difference - a deviation in the total energy use - between the most and least efficient design options showed the extent to which geometric factors can affect the energy use of the building. It was found that geometric factors could influence the energy use up to 32%. Furthermore, the recommended design options were classified according to their degree of energy performance for each of the climates.

The second group of strategies is related to the envelope design. To quantify their degree of influence, an existing tall office building was selected as a typical high-rise design for each of the climates and the energy use prior and after refurbishment was compared through computer simulations with DesignBuilder. The 21-storey EWI building in Delft, the Netherlands, is selected as the representative for the temperate climate and the 65-storey KOMTAR tower in George Town, Malaysia, for the tropical climate. As part of a sensitivity analysis, energy performance simulations defined façade parameters with higher impact on building energy consumption. A large number of computer simulations were run to evaluate the energy-saving potential of various envelope measures, as well as their combinations. The results showed which set of envelope measures suits each climate type best. Furthermore, it was found that the right combination of envelope strategies could reduce the total energy use of a conventional tall office building by around 42% in temperate climates and around 36% in tropical climates.

One other important difference between conventional and sustainable tall buildings is related to the application of natural ventilation. In this regard, the potential use of different natural ventilation strategies to reduce the energy demand for cooling and mechanical ventilation in high-rise buildings was investigated by using the same validated base models. The results showed that for a naturally ventilated tall office building in the temperate climate on average only 4% of the occupancy hours a supplementary air-conditioning system might be needed for providing thermal comfort during summer. For the tropical climate, the average percentage of discomfort hours (when air-conditioning is required to keep the indoor air temperature within the comfort limits) was around 16% of the occupancy hours during one year. In both climates, natural ventilation strategies could meet the minimum fresh air requirements needed for an office space for almost the entire period of occupancy hours; 96% in temperate climates and 98% in tropical climates.

The last important strategy that is becoming an integrated part of sustainable tall buildings is the use of greenery systems. The effects of greenery systems on the energy-efficiency, thermal comfort and indoor air quality of buildings were investigated by conducting a thorough literature review on five greenery concepts, including the green roof (GR), green wall (GW), green balcony (GB), sky garden (SG) and indoor sky garden (ISG). It was found that greenery systems have a limited impact for reducing the energy use of high-performance buildings. The maximum efficiency of greenery systems was reported during summer and for places with higher solar radiation and when integrated into buildings that have no solar control systems. However, other large-scale benefits for the urban environment (mitigation of CO2 concentration) and building residents (increased productivity and higher well-being) could justify the application of greenery systems as an essential sustainability feature for the design of tall office buildings.

To sum up, the architectural design is a determinant contributor to the performance of buildings and the comfort of occupants. The findings of this research were used to point out climate specific design strategies for tall office buildings in temperate and tropical climates. At the end of dissertation, a proposed model of an energy-efficient and comfortable high-rise office building for each of the investigated climates was illustrated. It is expected that the discussions and recommendations provided in this dissertation could form an acceptable starting point for improvements to tall building design and could be of assistance to make energy-wise decisions during the design process.

TOC

Samenvatting

Om het aantal niet effectieve ontwerpen te beperken heeft dit proefschrift de impact van architectonische ontwerpstrategieën op de energieprestatie van en op het thermisch comfort in kantoorhoogbouw in gematigde, subtropische en tropische klimaten onderzocht. Deze studie is gestart met een vergelijkend onderzoek tussen twaalf kantoortorens in de drie klimaatgroepen. Voor elk klimaat zijn drie duurzame kantoorgebouwen onderzocht en een gebouw dat representatief is voor de bestaande kantoorbouw in het betreffende klimaat. De effectiviteit van architectonische ontwerpstrategieën is onderzocht door een vergelijking te maken tussen de duurzame en representatieve kantoorgebouwen met betrekking tot hun potentieel effect op de behoefte aan verwarming, koeling, kunstverlichting en mechanische ventilatie. Sommige ontwerpstrategieën bleken een bepalende factor te zijn voor het minimaliseren van het energiegebruik van kantoorhoogbouw. Deze factoren kunnen worden gegroepeerd als geometrische factoren, gevelstrategieën, strategieën voor natuurlijke ventilatie en vegetatie. Simulaties zijn vervolgens uitgevoerd om te onderzoeken in welke mate deze factoren de energiebehoefte van en het thermisch comfort in kantoorhoogbouw beïnvloeden.

Om de impact te onderzoeken van de geometrische factoren zijn energiesimulaties uitgevoerd voor 12 verschillende vormen van de plattegrond, voor 7 verschillende plattegronddieptes, voor 4 gebouworiëntaties en voor diverse waarden van het glaspercentage in de gevel. De resultaten van het totaal jaarlijks energiegebruik (en de diverse eindgebruiken) zijn vervolgens gebruikt om de meest en minst efficiënte oplossingen te bepalen. De optimale ontwerpoplossing is die oplossing die op jaarbasis de som van het energiegebruik voor verwarming, koeling, kunstlicht en ventilatoren minimaliseert. Het procentuele verschil – ten opzichte van het totale energiegebruik – tussen de meest en minst efficiënte ontwerpopties toonde de mate waarin geometrische factoren het energiegebruik van het gebouw kunnen beïnvloeden. Geometrische factoren bleken het energiegebruik tot wel 32% te kunnen beïnvloeden. Bovendien zijn de aanbevolen ontwerpopties per klimaat geclassificeerd volgens hun mate waarin zij het energiegebruik beperken.

De tweede groep factoren is gerelateerd aan het ontwerp van de gevel. Om hun invloed te kwantificeren is per klimaat een bestaande kenmerkende kantoortoren geselecteerd en is het energiegebruik hiervan gesimuleerd met Design Builder. Vervolgens zijn op basis van energiesimulatie diverse gevelrenovatiemaatregelen onderzocht en gekwantificeerd. Het 21 verdiepingen hoge EWI gebouw in Delft, Nederland, was uitgekozen voor het gematigde klimaat; en de 65 verdiepingen hoge KOMTAR toren in

George Town, Maleisië, voor het tropische klimaat. Een sensitiviteitsanalyse bepaalde allereerst welke gevelvariabelen een grote invloed hadden op het energiegebruik van het gebouw. Vervolgens is een groot aantal computersimulaties uitgevoerd om het energiebesparingspotentieel van diverse gevelmaatregelen en hun combinaties te evalueren. De resultaten hebben laten zien welke set van maatregelen het beste geschikt is voor elk klimaat. Bovendien toonden de resultaten dat de juiste set van gevelmaatregelen het totale jaarlijkse energiegebruik van een conventionele kantoortoren met ongeveer 42% in een gematigd klimaat en met ongeveer 36% in een tropisch klimaat kan reduceren.

Een ander belangrijk verschil tussen conventionele en duurzame hoogbouw heeft betrekking op de toepassing van natuurlijke ventilatie. Het potentiele gebruik van verschillende natuurlijkeventilatiestrategieën om de energiebehoefte voor koeling en mechanische ventilatie in hoogbouw te beperken was daarom onderzocht met behulp van dezelfde gevalideerde modellen in Design Builder. De resultaten toonden dat voor natuurlijk geventileerde kantoorhoogbouw in een gematigd klimaat gemiddeld slechts 4% van de gebruiksuren een aanvullende airconditioning systeem nodig is om voor voldoende thermisch comfort te zorgen in de zomer. Voor een tropisch klimaat is het gemiddeld percentage discomfort uren (wanneer airconditioning nodig is) 16% van de gebruiksuren. In beide klimaten kunnen natuurlijkeventilatiestrategieën gedurende bijna de gehele gebruikstijd in een kantoor in de minimaal benodigde hoeveelheid verse lucht voorzien; 96% in een gematigd klimaat en 98% in een tropisch klimaat.

De laatste belangrijke factor als integraal onderdeel van duurzame hoogbouw is het gebruik groen. De effecten van groen op het energiegebruik, thermisch comfort en luchtkwaliteit zijn onderzocht door het uitvoeren van een literatuurstudie aangaande vijf groenconcepten: groene daken, groene gevels, groene balkons, 'sky gardens' buiten en 'sky gardens' binnen. Deze studie heeft laten zien dat de impact van groen op het reduceren van het energiegebruik van hoge prestatie gebouwen minimaal is. Het grootste effect van groen is gevonden voor de zomer, voor locaties met een hoge zonnestralingsintensiteit en voor gebouwen zonder zonwering. Echter, andere grootschalige voordelen voor de stedelijke omgeving (reduceren van de CO_2 concentratie) en voor de gebruikers van het gebouw (verhoogde productiviteit en hoger welzijn) zouden de toepassing van groen als essentieel duurzaamheidsonderdeel van kantoorhoogbouw kunnen rechtvaardigen.

Samengevat, het architectonisch ontwerp is een belangrijke factor die het energiegebruik van gebouwen en het comfort van de gebruikers bepaald. De resultaten van dit onderzoek hebben geleid tot klimaat specifieke ontwerpstrategieën voor kantoorhoogbouw in gematigde en tropische klimaten. Tot slot, is in het laatste hoofdstuk van dit proefschrift voor beide klimaten een model voor energie-efficiënte en comfortabele kantoorhoogbouw voorgesteld en geïllustreerd. Het is te verwachten dat de discussies en aanbevelingen volgend uit dit proefschrift een goed startpunt zullen vormen voor het verbeteren van kantoorhoogbouw en kunnen helpen bij het maken van goede beslissingen tijdens het ontwerpproces waarmee het energiegebruik kan worden verlaagd.

TOC

1 Introduction

§ 1.1 Background

The transition of the world population from a rural to an urban society has been a continuous and unstoppable process, which has characterized the world since the commencement of the Western European Industrial Revolution (Mumford, 1961). According to the United Nations (2014), the number of urban dwellers is expected to increase from 3.9 (in 2014) to 6.4 billion by 2050. In other words, about 65 million people are urbanizing every year, which is equivalent to the entire population of countries like France or the United Kingdom. One of the negative impacts of urban growth is climate change through the conversion of land uses (Meyer & Turner, 1992).

Sprawling cities and compact cities are the two most recognizable forms of urban growth (Jenks et al., 1996). The consequences of expanding cities through low-density suburbs is the increased dependence on automobiles, hence more consumption of fossil fuels and emission of greenhouse gases. In contrast, dense cities reduce the commuting distances from home to work, increase the viability of public transport and reduce the need for the spread of infrastructure networks due the concentration of different activities and diverse land uses (Thomas & Cousins, 1996). Although tall buildings are not the only solution to achieve high density, they are considered to be the best option for cities with limited land available for expansion (Yuen, 2005). In addition, high-rise buildings can accommodate more people on the same land than low-rise buildings. A smaller footprint by going upward leaves more space for parks and green spaces, which is an effective way to reduce the urban heat island effect.

The main driver for tall building development, however, can be addressed by its positive socio-economic benefits. Limited land and increasing prices, mature economies and the desire for global competition are important reasons for the increased construction of tall buildings (Watts, 2013). Nowadays, new plans for the densification of urban sites and implementation of new tall buildings are found all around the world, including North-American cities such as Chicago and New York, European cities, such as London, Paris, Frankfurt and Rotterdam as well as Southeast Asian cities such as Singapore, Kuala Lumpur and Bangkok. Despite the positive contribution that tall buildings can have for sustainable development, conventional tall (office) buildings have a greater environmental load (Dobbelsteen, 2012; Dobbelsteen et al., 2007) and they consume more energy per square meter than low-rise (office) buildings (Lam et al., 2004).

§ 1.2 Definition

There are many definitions for high-rise buildings that consider their height, number of stories and their usage (see Table 1.1). The Council of Tall Buildings and Urban Habitats (CTBUH, 2014) defines a high-rise as: “A building whose height creates different conditions in the design, construction, and use than those that exist in common buildings of a certain region and period”. For instance, a relatively small building may be considered a high-rise if it stands well above its built environment and changes the overall skyline. The maximum height of structures has progressed historically with building methods and technologies and thus what we today consider a high-rise is taller than before. According to CTBUH, a building that is over 14 stories (or more than 50 m in height), can be classified as a tall building. They further sub-divided tall buildings with significant height to supertall and megatall, which refers to buildings that are over 300 m and 600 m in height respectively. This research focuses on commercial forms of high-rise buildings that are between 50 to 300 m in height.

SOURCE	HIGH-RISE BUILDING	SKYSCRAPER
Britannica Concise Encyclopedia	Multi-story building tall enough to require the use of a system of mechanical vertical transportation such as elevators.	The skyscraper is a very tall high-rise building. The term originally applied to buildings of 10–20 stories, but now generally describes high-rises of more than 40–50 stories.
McGraw-Hill Dictionary of Architecture and Construction	A building having a large number of floors, usually constructed where land costs are high.	A very tall, multi-storeyed building, usually having curtain walls, so that the exterior walls are non-load-bearing, being supported independently at each floor by its skeleton-frame construction.
The American Heritage Dictionary of the English Language	Indicating or being a multi-storeyed building equipped with elevators.	
Wikipedia	A high-rise, tower block, apartment tower, office tower, apartment block, or block of flats, is a tall building or structure used as a residential and/or office building. In some areas they may be referred to as "MDU" standing for "Multi Dwelling Unit". These buildings are considered shorter than skyscrapers.	A tall, continuously habitable building of many stories, usually designed for office and commercial use. There is no official definition or height above which a building may be classified as a skyscraper though a building lower than about thirty stories is not likely to be a skyscraper and a building with fifty or more stories is certainly a skyscraper.
Emporis Standards	A multi-story structure between 35-100 meters tall, or a building of unknown height from 12-39 floors.	A multi-story building at least 100 meters tall.
Oxford English Dictionary	A tall modern building containing numerous floors of offices or flats (=tower block).	A very tall building of many stories.
United States General Laws (Salankar et al., 2016)	A building higher than 70 feet (21 m).	
Collins English Dictionary	A high-rise is a modern building which is very tall and has many levels or floors (=skyscraper, multi, multi-story).	A very tall multi-storey building (=tower).
Ken Yeang (1999)		The term skyscraper is used (in his book) as a convenient abbreviation for the large high-rise intensive building type, generally regarded as being over 10 stories and which can be of commercial, residential, hotel or mixed used.

TABLE 1.1 Definition of high-rise building and skyscraper.

§ 1.3 Problem statement

From the first generation of high-rise buildings in North America up to the present day, the architectural design of tall buildings has undergone a number of changes, influenced by regional regulations, new technologies and the worldwide energy crisis (Gonçalves, 2010). Historically, architectural forms followed passive design solutions to provide desirable internal conditions. From the 1950s, air conditioning became a key element in high-rise office design, enabling architects to test new design opportunities (i.e. curtain wall and deep plan), as a result of which the external climate conditions were no longer a limiting factor that influenced the design (Fenske, 2013). The formation of sealed glass boxes with deep floor plates increased the dependency of tall office buildings on air conditioning and artificial lighting. This model of high-rise typology became the representative of an international style of the modern movement and of economic wealth and spread throughout the world regardless of climatic and contextual differences.

With the emergence of the energy crisis in the 1970s, and following that, the rise of an environmental consciousness in the 1980s and 1990s, energy-saving measures and sustainable buildings became a topic of attention (Gonçalves, 2010). In response to increasing global pressure for improving the environmental performance of buildings, the European Union suggested a roadmap to cut the CO_2 emissions from houses and office buildings by around 90% below 1990 levels by 2050 (European Commision). In line with that, many green building assessment systems have been established globally, with the aim to encourage the construction market to develop greener buildings with lower energy consumption. In spite of the advances in the construction industry and the raising awareness of the contribution of the building sector to climate change and global warming, the question arises why there are few built examples of well-performing tall buildings – even the Commerzbank building, considered an ecological high-rise, had a higher environmental load than low-rise alternatives (Colaleo, 2003) – and why there is little interest to release the operational data of such buildings into the public domain.

The common criticism is associated with poor architectural design, which makes tall buildings intense energy consumers. In order to have high-performance tall buildings, first there is a need to reduce the building's demand for energy and the most straightforward approach is to design them in a way that reduces their appetite for energy. However, energy-efficiency is often demonstrated by high-performance appliances and technologies (e.g. lighting, HVAC systems, and elevators) rather than the design in the first place. For building projects for which the architectural design is not optimally treated as an integral part of environmental design at the outset of a

TOC

project, the potential for energy saving is limited. Increasing the awareness about the importance of architectural design strategies for reducing the energy use in buildings can limit the number of ineffective designs.

Furthermore, an environmentally responsive architecture can add value beyond what energy saving could offer. The Green Building Council Austrlia (2006) identified key economic benefits that green buildings could deliver to building developers, owners and tenants (see Table 1.2). Market differentiation, improved return on investment, higher occupancy rate, and increased staff productivity are among the benefits that green buildings can offer. In another study, the results of annual expenses breakdown for a group of typical commercial buildings in North America showed that staff salaries dominantly outweighed other costs including those involved with the maintenance (1%), utilities (1%), taxes (1%) and rent (9%) (Lucuik et al., 2005). This indicates that a small increase in productivity can have large economic benefits. A Californian study found that up to 20% improvement in staff performance can be achieved through enhancing the physical comfort conditions of indoor environment including daylight, ventilation, view and temperature. Therefore, the benefits of environmental design are numerous and of paramount importance and they outweigh the increased initial costs and reduced lettable floor area that is typically associated with designing well-performing commercial buildings (Eichholtz et al., 2013).

FOR BUILDING DEVELOPERS	FOR OWNERS/OCCUPANTS
Enhanced ability to rent or sell building	Improved public image
Improved occupancy rates: 3.5% higher	Up to 60% reduction in water and energy consumption
Higher rents: 5-10% increase	Superior thermal, indoor air and lighting quality
Increased asset value: 10% increase	Increased occupant satisfaction and productivity: up to 25% annually
Improved return on investment: minimum 14%	

TABLE 1.2 Economic benefits of using an environmental design as opposed to a conventional design for commercial buildings. Adapted from (Green Building Council Australia, 2006).

§ 1.4 Research objectives

The principal objectives of this dissertation are:

- to explore the impact of architectural design strategies on energy consumption and thermal comfort of tall office buildings in temperate, sub-tropical and tropical climates
- and based upon these results, to develop recommendations for high-rise office building design in temperate and tropical climates to support designers in the decision-making process

§ 1.5 Boundary conditions

Comparing the Köppen-Geiger climate classification world map with a map showing the distribution of high-rise buildings around the globe, it can be observed that the majority of high-rise buildings have been constructed in cities with temperate, sub-tropical and tropical climates. The outdoor air temperature in sub-tropical climates is close to the comfort temperature of humans throughout the course of the year so that the required energy for space conditioning is typically lower than in the other two climates. Furthermore, the results of energy simulations confirmed this claim because the impact of architectural design strategies on building energy use was lower in absolute value. Furthermore, the majority of design strategies that was found to be effective for the building envelope in the tropical climate can be used with only minor changes for the sub-tropical climate. For this reason, the sub-tropical climate will not be thoroughly discussed in this dissertation and the area of investigation is mainly limited to certain design strategies that may have a greater impact on energy use such as geometry factors (chapter 3). As a result, the main focus of this research and the development of design recommendations will be for two climates −namely temperate and tropical− in which the design could have a greater influence on building energy use.

In this research, the focus of investigation is on one particular form of buildings, the high-rise office typology, which is believed to reflect a higher concern. Recent studies showed that the commercial sector, and in particular the office sub-sector, offers the greatest potential for energy saving as it is a significant contributor to energy use and carbon emissions (Wade et al., 2003). From the commercial perspective, office buildings offer higher returns than other types of properties, so the risk of investment is lower and therefore there is a greater desire for investing in innovative design strategies among building developers and building owners (Green Building Council Austrlia,

TOC

2006). Besides, the integration of passive design techniques into an office building could be more challenging for designers (due to larger floor plate depths, higher internal gains, higher lighting demand and the special arrangement of internal spaces); hence, further study is needed on this topic.

Apart from that, the high-rise typology is different from the low-rise one in terms of the influential parameters that affect the building performance so that the design should be tailored to the specific requirements of high-rises. An increase of the building height can induce the stack effect which increases the amount of infiltration and heat loss through the building façade. This can possibly influence the optimal size of openings and the insulation properties of the envelope. On the positive side, the excessive height can be used to assist natural ventilation using vertical shafts. Another difference that can cause design differences is related to climatic parameters that change with height. With the increase of the building height, the air temperature tends to slightly drop and the wind speed get higher. As a result, the upper floors may need lower amounts of cooling energy in summer but higher amounts of heating energy in winter as compared to the base floors. The high wind speed and difficult accessibility, in addition, may limit or make unfeasible the application of certain design elements. Considering the urban context, the building form and orientation should be adjusted according to adjacent buildings, as they can influence the solar gains and wind flow patterns to a large extent. The residents of conventional tall buildings have a stronger feeling of being disconnected from the outside environment which may affect their productivity and well-being. The amount of internal gains is higher in high-rise buildings, which can influence the amount of energy use for cooling and heating compared to their mid- or low-rise equivalents. A higher percentage of space should be allocated to the circulation spaces and structural components which can result in lower space efficiency. For effective daylighting and natural ventilation, certain design elements are required; however, fire safety regulations should be addressed as well. All these factors indicate the importance of this particular building typology, so that further investigation is required.

The main aim of this research is to reduce the energy demand of tall office buildings through architectural design. To achieve high levels of energy-saving, however, it is important to acquire a good understanding of how architectural design strategies can influence the total energy use (and different energy end-uses) individually and as a group. Energy simulations, if well-validated, can help us to correctly apply design strategies to achieve considerable energy-savings.

TOC

§ 1.6 Research questions

Main question

Following these objectives, the main research questions are formulated as:

- To what extent do architectural design strategies affect energy consumption of and thermal comfort in high-rise office buildings in temperate, sub-tropical and tropical climates?
- What design factors should be focused on during the decision-making process to achieve a high-performance design in temperate and tropical climates?
- In order to properly address the main research question, the following background and sub-questions need to be answered:

Background questions

Q.1a: What is the best method to quantify the impact of architectural design strategies on energy consumption and thermal comfort of high-rise buildings?
Q.1b: How can architects benefit from the results of this study for improving the performance of high-rise office buildings?

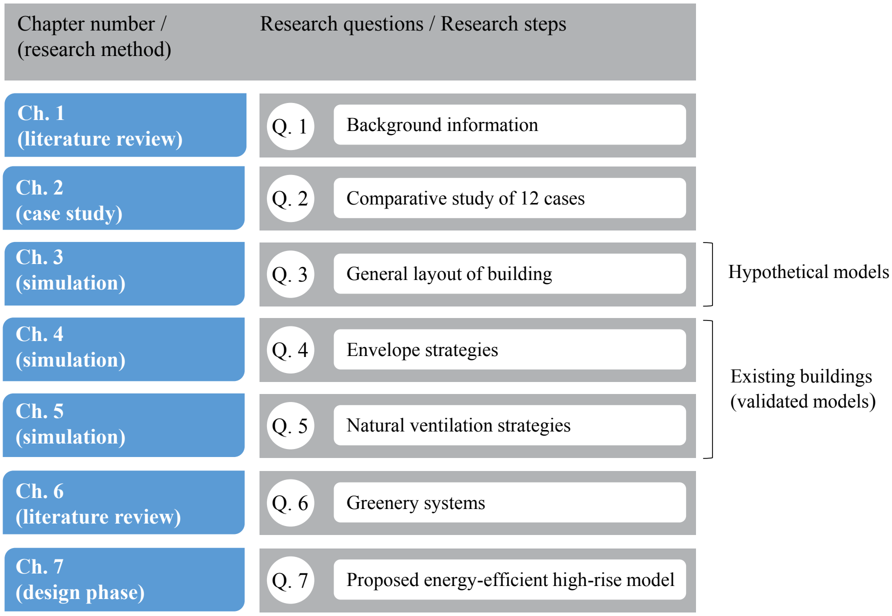
Sub-questions

Q.2: What are the design differences between a typical and sustainable high-rise office buildings in temperate, sub-tropical and tropical climates?
Q.3: To what extent do geometric factors affect the energy-efficiency of high-rise office buildings?
Q.4: To what extent do envelope design strategies affect the energy-efficiency of high-rise office buildings?
Q.5: To what extent do natural ventilation strategies affect energy-efficiency of and thermal comfort in high-rise office buildings?
Q.6: To what extent do greenery systems affect the energy-efficiency, thermal comfort and indoor air quality of high-rise office buildings?
Q.7: What are the essential architectural design features for high-rise office buildings' energy-efficiency in temperate and tropical climates?

§ 1.7 Research method

§ 1.7.1 Research steps and approaches

The main focus of this research is to assess the performance of architectural design strategies for energy-efficiency of tall office buildings, and based on these results, develop recommendations for designers of high-rise office buildings in temperate and tropical climates. This dissertation implements three data collection methods to address the research objectives and questions: a) literature review, b) case study, c) simulation-based performance analysis. Afterwards, a summary of the recommended design strategies is provided for temperate and tropical climates. Finally, through a design phase, a three-dimensional model of an energy-efficient high-rise office building is suggested for each of the two climates. The schematic representation of research steps and approaches is presented in Figure 1.1.



Chapter number / (research method)	Research questions / Research steps		
Ch. 1 (literature review)	Q. 1	Background information	
Ch. 2 (case study)	Q. 2	Comparative study of 12 cases	
Ch. 3 (simulation)	Q. 3	General layout of building	Hypothetical models
Ch. 4 (simulation)	Q. 4	Envelope strategies	Existing buildings (validated models)
Ch. 5 (simulation)	Q. 5	Natural ventilation strategies	
Ch. 6 (literature review)	Q. 6	Greenery systems	
Ch. 7 (design phase)	Q. 7	Proposed energy-efficient high-rise model	

FIGURE 1.1 Scheme of research steps and methods, and the connection with main research questions.

a) To address two research questions (Q.1 and Q.6), data and information was merely gathered through a literature search. The introduction chapter provides some background information about the evolution of high-rise buildings and the key factors affecting their design historically. Later on, chapter 6 provides an in-depth literature review for different greening systems with respect to their energy impact. For two reasons the literature search was selected among other methods to investigate the contribution of greenery systems on energy-saving. Firstly, a simulation tool that can accurately calculate the evapotranspiration and shading effect of vegetation together and for both of the vertical and horizontal greening systems was not available at the time of investigation. Secondly, the results of previous experimental studies showed the extent of energy saving from the application of greenery systems is very limited compared to other strategies (related to architectural design), therefore does not merit further experimental investigation. However, other large-scale benefits for the urban environment (mitigation of CO_2 concentration) and building residents (increased productivity and higher well-being) could justify the application of greenery systems as an essential sustainability feature for the design of tall office buildings. As a result, chapter 6 is allocated to the study of different greenery systems (in terms of energy-saving, indoor air quality, thermal comfort and other factors) through a review of past research.

b) In order to address the design differences between a typical and a sustainable high-rise office building (Q.3), twelve case buildings were selected with different degrees of sustainability performance, from three climate types (temperate, sub-tropical & tropical). For each climate group, there were three sustainable high-rises and one typical high-rise design as a reference. Building-related energy performance data were collected through contact with the energy consultants involved in the respective building and using data from secondary (literature) sources. The total energy use (and different energy end-uses) of each group of buildings in one climate (four cases) were compared together, and also with the energy benchmarks, to analyse the effectiveness of different design strategies in the specific climate type. Comfort requirements of different climates/cases and the impact that they might have on energy use were discussed as well. Finally, lessons from these buildings were defined for the three climates. Design strategies under four categories were identified for further investigation including: (1) geometric factors, (2) envelope measures, (3) natural ventilation, and (4) greenery systems. For the first three categories, simulation-based studies were conducted, while for the last one, a literature review was done.

c) Simulation studies (CFD studies, parameter studies and sensitivity analyses) were carried out to quantify the impact of geometric factors (Q.4), envelope elements (Q.5) and natural ventilation strategies (Q.6) on building energy performance and thermal comfort by using hypothetical building models or existing buildings. The DesignBuilder (version 3.4 and 4.7) interface for EnergyPlus was used as a performance assessment tool. For the investigation on building general layout, hypothetical building models (40-storey) were incorporated in three climate contexts: Amsterdam (temperate), Sydney (sub-tropical) and Singapore (tropical). However, for the investigation of envelope elements and natural ventilation strategies, existing tall office buildings were selected as typical high-rise designs in temperate and tropical climates; these were modelled in DesignBuilder. The EWI building (21-storey) in Delft, the Netherlands, was selected as the representative for the temperate climate and the KOMTAR tower (65-storey) in George Town, Malaysia, for the tropical climate. The models of these buildings in DesignBuilder were validated by comparing measured and simulated annual and monthly energy use intensity (EUI) of the buildings for one year. The measured data were obtained from the literature in case of the KOMTAR tower or from the building management in case of the EWI building.

In chapter 5, the potential use of natural ventilation (NV) strategies to reduce the energy demand for cooling and mechanical ventilation for high-rise buildings was investigated by using the same validated base models from chapter 4. The investigation of natural ventilation (NV) strategies comprised of two main steps: (1) the study of the impact of natural ventilation strategies on indoor comfort indicators including thermal comfort and fresh air during the operation of natural ventilation by using EnergyPlus; and (2) the study of the indoor air temperature and the velocity contours under different weather scenarios (during typical and extreme weather conditions) by using Computational Fluid Dynamics (CFD). Further details on the methodology will be provided in each respective chapter.

§ 1.7.2 Simulation tool

There is common agreement that: “building performance simulations are an integral part of the design process for energy-efficient and high-performance buildings, since they help in investigating design options and assess the environmental and energy impacts of design decisions” (Aksamija, 2012, p. 1). There is an increasing number of simulation tools available, capable of running complex calculations by using rigorous approaches. In all energy simulations, there are four main steps that needs to be performed; creation of the model, setting up inputs, validation of the model, and analysis of results. DesignBuilder’s fully-integrated approach provides this possibility to develop one core model and use it to run a variety of assessments using different engines (EnergyPlus and CFD). The intuitive structure allows to run simulations for large complex buildings with minimum tendency to crash. The well-structured

TOC

graphical interface and data management tools of DesignBuilder make it a much easier tool for building simulation users, while the power and flexibility of EnergyPlus, the underlying simulation engine, enhances the reliability of results.

Energy calculation

As a result, the DesignBuilder interface for EnergyPlus was used as a building energy performance simulation tool to create the models. DesignBuilder is a validated tool that has passed Building Energy Simulation Tests (BESTest) according to the ISO 13790 (2008) standard for the calculation of energy use for space heating and cooling and the ANSI/ASHRAE Standard 140 (2011) for building thermal envelope and fabric loads.

Computational Fluid Dynamics (CFD)

The air flow rate and the temperature distribution in the building were simulated with the help of CFD. In this study, the CFD code from DesignBuilder was employed. The most widely used and tested turbulence model, k-ε turbulence model, was selected which belongs to the RANS family of models. The DesignBuilder’s CFD code has been validated by a number of studies through a comparison with measured data from existing buildings (Baharvand et al., 2013; Chung et al., 2014) and also in comparison with the generated results from other CFD packages (Northumbria University, 2011). Using the CFD package in DesignBuilder simplifies the input of boundary conditions, since there is the possibility of using previously calculated quantities of temperatures, heat flows and flow rates from the airflow network model in EnergyPlus.

§ 1.8 Research outline

The schematic representation of the dissertation outline is presented in Figure 1.2.

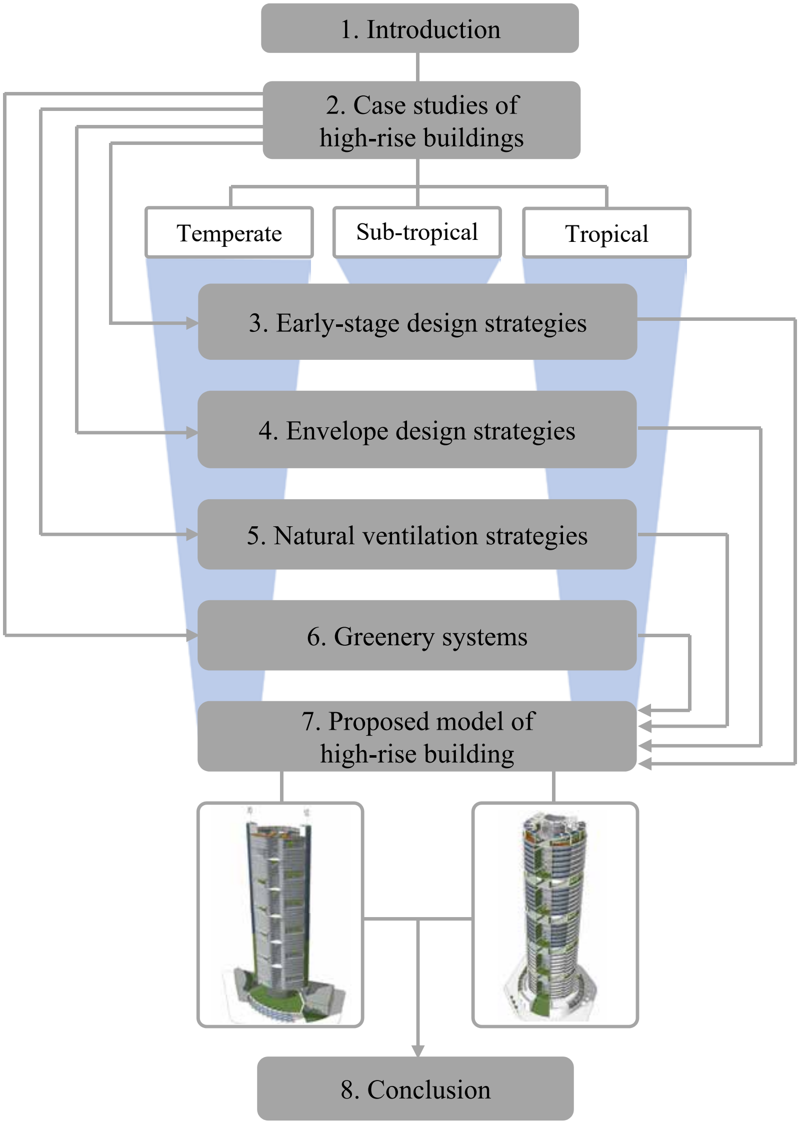


FIGURE 1.2 The outline of dissertation.

Chapter 2) On the basis of a case-study approach with multiple cases (12 case buildings), chapter 2 compares the effectiveness of implemented design strategies between high-performance (sustainable) and low-performance (conventional) existing examples of high-rise buildings in three climates; temperate, sub-tropical and tropical. The energy data of each group of buildings in one climate (four cases) is collected to analyse the effectiveness of different design strategies in the specific climate type. Furthermore, a comparison with international benchmarks shows the effectiveness of design strategies for each climate. This research showed which design strategies are more effective for sustainable high-rises to reduce the energy consumption for cooling, heating, ventilation and lighting and which ones should be avoided (based on the reference conventional examples).

Chapter 3) Decisions made at early stages of the design are of the utmost importance for the energy-efficiency of buildings. Using extensive parametric energy simulations, chapter 3 investigates the impact of geometric factors for the energy-efficiency of high-rise office buildings in three climatic contexts: Amsterdam (temperate), Sydney (sub-tropical) and Singapore (tropical). The investigation is carried out on 12 plan shapes, 7 plan depths, 4 building orientations and discrete values for window-to-wall ratio, using hypothetical models of tall buildings with a total floor area of 60,000 m^2 distributed over 40 storeys with identical floor plans.

Chapter 4) The building envelope is the interface between the interior of the building and the outdoor environment. A building's energy consumption to a large extent depends on certain envelope design elements. Chapter 4 aims to find energy-saving solutions for the envelope design of high-rise office buildings in temperate and tropical climates. For this purpose, an existing tall office building is selected as a typical high-rise design in each of the two climates and the energy use prior and after refurbishment is compared through computer simulations. By taking the base case as a reference and optimising one parameter at each step, this study resulted in a high-performance envelope design that offers a considerable energy-saving.

Chapter 5) Chapter 5 investigates the potential use of natural ventilation strategies to reduce the energy demand for cooling and mechanical ventilation for high-rise buildings. Different natural ventilation scenarios are developed for the base design (using the same validated base models from previous chapter) and the CFD package in DesignBuilder is used to predict air velocity and temperature distribution under different weather conditions. The operative temperature and the total fresh air changes per hour are calculated with EnergyPlus and are compared accordingly with the local comfort standards. The percentage of discomfort hours indicates when a ventilation system would need active cooling or mechanical ventilation. In tropical climates, the potential benefits of elevated velocities for improving thermal comfort is additionally investigated.

TOC

Chapter 6) Greenery systems are among the essential sustainability features for the environmental design of tall buildings. Chapter 6 provides a literature review on different greenery systems and the potential energy benefits that they can offer to a building. Furthermore, the suitability of different greenery systems for different climate types is discussed.

Chapter 7) Chapter 7 consolidates the findings from previous chapters to point out general and climate-specific design strategies that are required for energy-efficiency of tall office buildings. The outcomes will be used by the end of this chapter to illustrate a proposal for an energy-efficient high-rise office building in the temperate and tropical climates.

Chapter 8) Finally, the main highlights and recommendations are concluded in chapter 8.

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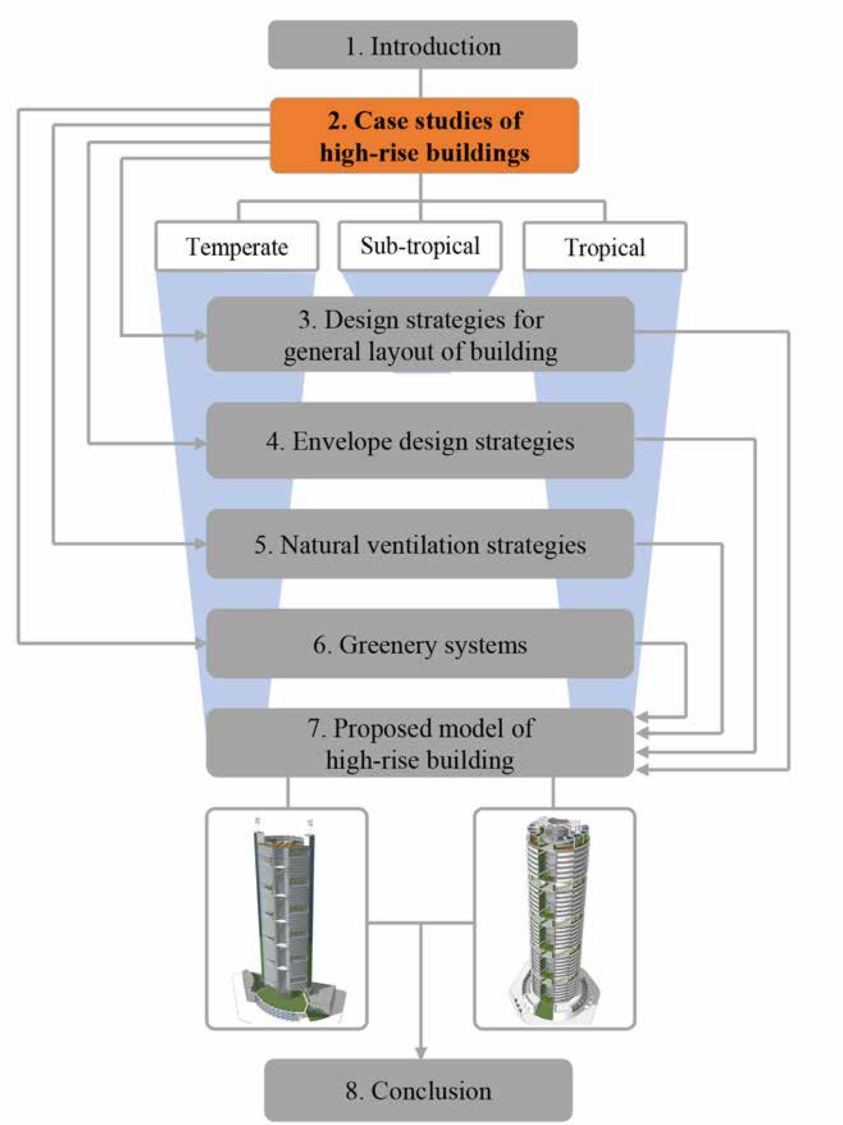
TOC


1. Introduction
2. Case studies of high-rise buildings
Temperate
Sub-tropical
Tropical
3. Design strategies for general layout of building
4. Envelope design strategies
5. Natural ventilation strategies
6. Greenery systems
7. Proposed model of high-rise building
8. Conclusion

2 Case studies of high-rise buildings

In the previous chapter, tall buildings in their current form of design were criticised for their contribution on the intensification of the urban heat island (UHI) effect. It was hypothesized that poor architectural design – either due to the lack of knowledge by architects or the existing traditional commercial attitudes by developers – is a major factor in making tall buildings intense energy consumers; hence further investigation should be carried out. As the starting-point of this research, this chapter aims to distinguish the main design principles that are incorporated in sustainable and conventional high-rises. In this regard, a comparative study between nine sustainable and three conventional high-rise office buildings in three climate groups (temperate, sub-tropical & tropical) concerning their energy performance and the use of architectural design strategies is conducted. For each category of climates, the effectiveness of different design strategies for reducing the cooling, heating, ventilation and electric lighting energy demands are analysed (in sections 2.3-2.5). Lessons from these buildings (both general and climate specific) are defined in section 2.6. Afterwards, the energy use intensity (EUI) of twelve case studies is compared to related energy benchmarks in each climate/context. In Section 2.8, the mean monthly outdoor air temperature of each case is compared to comfort temperatures based on adaptive thermal comfort (ATC) models versus predicted mean vote (PMV) models. Finally, a general discussion of findings is provided in section 2.9.

A comparative study: Design strategies for energy-efficiency of high-rise office buildings[1]

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Abstract

Tall buildings are being designed and built across a wide range of cities. A poorly designed tall building can tremendously increase the building's appetite for energy. Therefore, this paper aims to determine the design strategies that help a high-rise office building to be more energy efficient. For this purpose, a comparative study on twelve case buildings in three climate groups (temperate, sub-tropical & tropical) was performed. The exterior envelope, building form and orientation, service core placement, plan layout, and special design elements like atria and sky gardens were the subject of investigation. The effectiveness of different design strategies for reducing the cooling, heating, ventilation and electric lighting energy were analysed. Finally, lessons from these buildings were defined for the three climates. Furthermore, a comparison of building energy performance data with international benchmarks confirmed that in temperate and sub-tropical climates sustainable design strategies for high-rise buildings were performing well, as a result leading to lower energy consumption. However, for the tropics the design of high-rise buildings needs higher concern.

Keywords

Design strategies for energy efficient tall buildings, building energy performance, sustainability and climate type.

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TOC

§ 2.1 Introduction

The construction of tall buildings in our modern cities is increasing in response to several socio-economic and environmental issues. Urban population growth and preservation of green areas, limited land and increasing prices, mature economies and the desire for global competition are some of the reasons for the increased tall building construction. Despite environmental concerns over energy scarcity and global warming, many low-performance tall buildings are emerging to provide cities with additional floor area. These typical air-conditioned glass boxes are not energy efficient in many aspects of their design. This will result in buildings with a high appetite for energy.

Few studies have investigated the impact of design strategies on the energy consumption of high-rise office buildings. Ismail (2007) conducted a comparative study of six Malaysian high-rise buildings (three bioclimatic and three conventional) to investigate the effect of bioclimatic design strategies on users' perception of the indoor environment and on building-related energy use. They found that bioclimatic buildings offer more indoor comfort, improve user's satisfaction and use less energy. In another study, Jahnkassim & Ip (2006), modelled and simulated three bioclimatic high-rises, which were designed by Malaysian architect Ken Yeang, to determine the impact of different design strategies on energy-saving. Comparing the results between the simplified high-rise model (generic option) and bioclimatic model (as designed), they found that the highest energy-saving could be achieved by placing the service core on the hot side and by using external shading devices. The impact of vegetation on energy consumption, they found, was limited to around 0.4% (only including the shading effect of outdoor vegetation and not the evaporative cooling effect). Furthermore, for one of the bioclimatic buildings (Menara Mesiniaga), the impact of recessed sky courts was reported to be negative, adding to the cooling demand.

There is thus still a lack of in-depth studies into the design strategies that can make tall buildings more energy efficient. This paper, therefore, describes the results of a case-study based on multiple high-rise buildings in order to ascertain design strategies that help a high-rise building to be more energy efficient in a temperate, a sub-tropical and a tropical climate. In order to have high performance tall buildings, first there is a need to reduce the building's demand for energy and the most straight forward approach is to design them in a way that reduces their appetite for energy.

TOC

§ 2.2 Methodology

This paper is an extension of work originally reported in the Proceedings of the International Conference on Passive and Low Energy Architecture (PLEA) on 6 case buildings and two climate types (Raji et al., 2014). As presented in Figure 2.1, the extended version comprises of twelve case buildings with different degree of sustainability from three climate types (temperate, sub-tropical & tropical) and follows a holistic case-study design with multiple-cases (Yin, 2009). For each climate group, three sustainable high-rises were selected and one typical high-rise design as a reference. This replication logic increased the external validity of this study.

Among others, multiple sources of evidence were used to increase construct validity: building-related energy performance data was collected through a literature review and contact with the energy consultants. The energy data of each group of buildings in one climate (four cases) was compared to analyse the effectiveness of different design strategies in the specific climate type. Finally, lessons from these buildings were defined for the three climates. Furthermore, a comparison with international benchmarks shows the effectiveness of design strategies for each climate. The selection criteria for the sustainable cases were:

- Considered by one of the rating systems or standards for high-performance buildings
- Availability of building-related energy performance data (metered or simulated)
- Newly constructed office building that has been occupied for two years with at least fifteen floors

Definitions and methods for calculating the energy use intensity (EUI) vary among countries and legislations. This may cause difficulties when comparing buildings in different countries on energy performance. A building's EUI can be presented in two forms: source energy (primary energy) and site energy (delivered energy). Source energy defines the level of CO_2 emission associated with the energy consumption in a building. Therefore, in some cases, where the energy comes from different sources (renewables or fossil fuels), the primary energy can provide a better understanding of the building's environmental impact. While many other cases use simply site energy. Furthermore, the calculation methods of EUI differ based on the selected floor area. It can be a fraction of the total gross floor area or the net floor area of a building. In this study, we tried to take these differences into account by normalizing the EUI figures among all cases. In this respect, a few conversions were made for making the energy figures comparable. The presented energy figures in this paper, therefore, are site energy in kWh/m^2 of gross floor area.

TOC

Considering the fact that a building's energy performance can be influenced by the decisions made after the construction and the user's behaviour during occupation, the best way to quantify the energy efficiency of a building is by measuring the energy consumption after a certain period of occupation (minimum two years) when the building's operation is balanced appropriately (Gonçalves & Umakoshi, 2010). It is quite probable that when there is a mismatch between the measured and simulated energy performance of a building the influence of the human factor on modelling results was not taken into account. Knowing this fact, this paper aims to focus on case buildings with available measured data. However, buildings' energy performance based on the measured data are either not always available or made publicly accessible. As a result, if measured energy consumption for a building are absent, simulated data are used instead. And where it may impact findings, it is discussed and acknowledged in wthe comparative conclusions.

FIGURE 2.1 Classification of 12 case buildings in temperate, sub-tropical and tropical climate.

ICONOGRAPHY

	Double-skin façade	MO	Manually operated
	Triple-glazed façade		Central atrium or void
	Double-glazed façade		Peripheral atrium
	Single-glazed façade		Indoor sky garden
	Natural ventilation		Sky garden
	Extracted air from indoor		Rooftop shading
	Single-sided and/or cross ventilation + Stack ventilation		Recessed balcony
	Cross ventilation		Recessed green balcony
	Indoor blind within the cavity	+ –	Aerodynamic building form
	Indoor blind		Non-aerodynamic building form
	External shading		Environmentally oriented
Auto	Automatically operated	/	Compact building form

SUBSCRIPTS

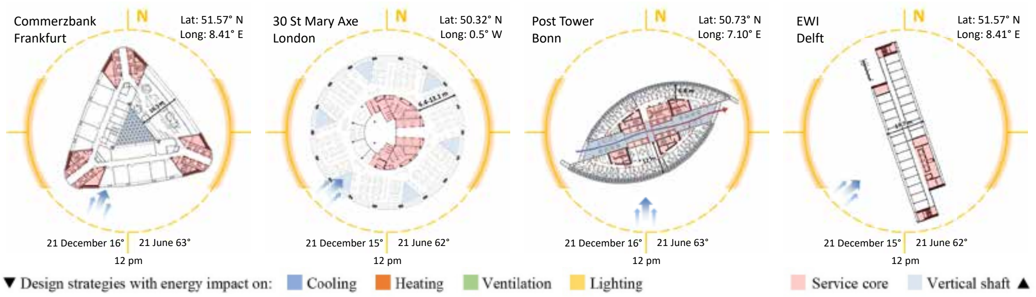
AHU: Air-handling unit
BMS: Building management system
CFD: Computational fluid dynamics
DSF: Double-skin façade
EUI: Energy use intensity
GB: Green balcony

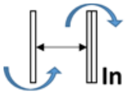
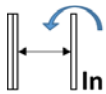
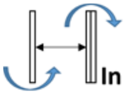
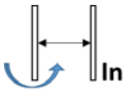
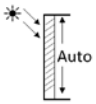
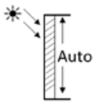
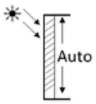
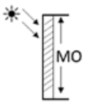
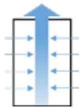
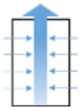
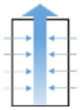
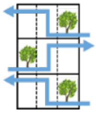
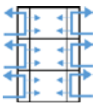
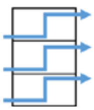
ISG: Indoor sky garden
NT: Natural ventilation
SG: Sky garden
SSV: Single-sided ventilation
WWR: Window-to-wall ratio

TOC

§ 2.3 Temperate climate

A comparison of design strategies and energy consumption data for the case buildings in the temperate climate are presented in Figure 2.2 and 2.3 respectively.



Energy impact				Strategies / Cases	Commerzbank	30 St. Mary Axe	Post Tower	EWI
🟦	🟧	🟩	🟨	Façade type				
🟦	🟧		🟨	Shading				
		🟩		NV type				None
🟦		🟩		Design strategies assisting in NV				None
🟦	🟧		🟨	Window-to-wall ratio	58%	100%	100%	80%

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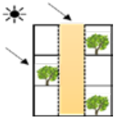
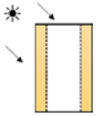
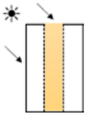
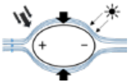
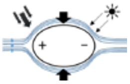
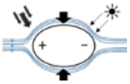
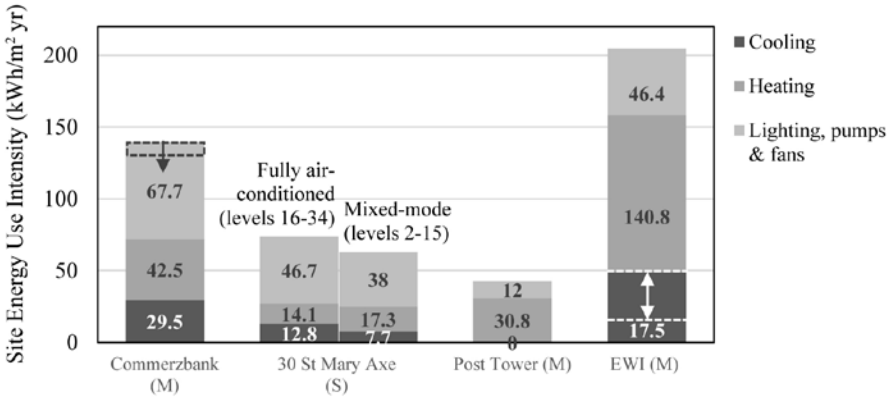
Energy impact				Strategies / Cases	Commerzbank	30 St. Mary Axe	Post Tower	EWI
			🟨	Design strategies assisting in daylight control				None
		🟩	🟨	Service core placement				
🟦		🟩		Building form and orientation				
		🟩		Plan layout	Cellular	Mixed	Cellular	Cellular
		🟩	🟨	Plan depth	16.5 m from void	6.4-13.1 m from core	12 m from void	17.7 m between facades
🟦	🟧	🟩	🟨	Control of indoor climate	BMS & Occupant	BMS & Occupant	BMS & Occupant	Occupant (limited)
	🟧			Thermal buffer spaces	0.2 m DSF cavity	1-1.4 m DSF cavity	1.2-1.7 m DSF cavity	0.95 m DSF cavity
🟦		🟩		Summer nighttime NV	✓	✗	✓	✗
		🟩		Mixed-mode vent	✓	✗	✓	✗
🟦				Greenery system	ISG	✗	✗	✗
🟦	🟧			Internal zones with different temp	✓	✗	✓	✗

FIGURE 2.2 A comparative study of design strategies for case buildings in the temperate climate.

TOC



(S)=Simulated; (M)=Metered; the electricity consumption is just for lighting, pumps and fans. [1]The EUI for the Commerzbank (Goncalves & Bode, 2010) and the Post Tower (S. Reuss 2014, pers. comm. 19 May) were originally calculated based on the net floor area. To convert the figures from net to gross floor area an efficiency factor (net area/gross area) of 61% & 57% is considered respectively for Commerzbank and Post Tower. In addition, a very small amount of the cooling load is combined with the electricity usage in the Commerzbank building that should be negligible. [2]The energy consumption at 30 St Mary Axe (N. Clark 2014, pers. comm. 12 May) is based on simulations of two scenarios: a fully air-conditioned design on levels 16-34 and a mixed-mode design on levels 2-15. The energy source at EWI building is provided by electricity from the grid, district heating and a ground-coupled heat pump system (W. van Rijsbergen 2014, pers. comm. 4 Aug).
Detailed information regarding the weather file, heating degree days (HDD) and cooling degree days (CDD) of each case study/city are presented in the table below.

CASE STUDY / CITY	COMMERZBANK / FRANKFURT	30 ST MARY AXE / LONDON	POST TOWER / BONN	EWI / DELFT
Year	2008	IWEC*	2003	2013
HDD	2750	2300	2786	2631
CDD	396	185	269	184

*IWEC: International Weather for Energy Calculation (US Department of Energy). *For energy simulations, a dynamic method based on hourly values was employed and the energy results were generated from IWEC weather data for each location. HDD and CDD data were obtained from BizEE Software Ltd.*

FIGURE 2.3 Energy performance data of the temperate cases for one year.

Cooling

Among the cases studied in a temperate climate, the Post Tower has the lowest energy consumption for cooling from the grid by around zero. Thermally active ceilings and decentralized supplementary fan coil systems provide cooling for this building. The cold water required for cooling is supplied by the Rhine River and a sunk well. This eliminates the need for cooling by chillers. The electricity to drive the pumps is the only requirement for providing cooling (Welfonder, 2006). Furthermore, the building is oriented based on the sun path with the long axis almost along east-west which reduces the solar heat gain. Mary Axe can be ranked second best, with an electricity consumption in a range between 7.7-12.8 kWh/m^2 for cooling. The energy consultants for this building have considered two scenarios for air-conditioning, a mixed-mode zone (a combination of mechanical and natural ventilation during different times a year) and a fully mechanically conditioned zone, respectively for the levels 2-15 and 16-34. The simulated results show that the cooling demand is lower for the mixed mode zone (7.7 kWh/m^2) compared to entirely mechanically conditioned zone (12.8 kWh/m^2). Commerzbank's energy consumption for cooling is around 29.5 kWh/m^2. Absorption chillers generate cold water and chilled ceilings distribute this above the conditioned spaces. In addition, the building uses natural ventilation up to 80% of the year which reduces the need for air-conditioning effectively. Commerzbank and Post Tower are also equipped with other energy-efficiency strategies such as a double-skin façade with ventilated cavity, motorized blinds for solar control, and summer night-time ventilation. A building management system (BMS) controls the operation of blinds and openings, which can be overridden by the occupants to customize the climate to their desires. The total energy consumption of all of the 3 sustainable buildings is considerably less than of typical air-conditioned buildings in the same climate.

In contract, the EWI building of Delft University of Technology is a conventional high-rise building. The building has benefitted from some of the features of sustainable buildings, like a narrow plan and a double-skin façade. On the other hand, inefficient natural ventilation inside the cavity of the double-skin facade and no operable windows limit the effectiveness of these strategies. Cooling is generated by a ground-coupled heat pump system. Cold water is used to cool air in plant rooms which is then distributed to cellular offices. Backup air-handling units (AHUs) are used for spaces with higher cooling demand like lecture halls and labs. Since the air supply ducts are placed inside the cavity of the double-skin facade, the chilled air is pre-heated along its way to the rooms. Therefore, the efficiency of this cooling system is low and as a result, the electricity demand for cooling high. For solar protection, Venetian indoor blinds are adjusted in the cavity and occupants can control manually the radiation intensity in each office. Since the energy use for cooling is partly being provided by the ground-coupled heat pump system (17.5 kWh/m^2) and the rest by the city grid, the total consumption for cooling is unknown. However, the mild summers in Delft lead to a low cooling demand of this building.

TOC

Heading

Considering heating, the Mary Axe building has the lowest energy consumption among the temperate cases. Fresh air for mechanical ventilation is drawn through the narrow slits between the glazing panels, then conditioned by the AHUs and finally distributed through adjusted ducts at ceiling level. Part of the exhaust air from the offices ventilates the cavity inside the facade (Jenkins, 2009); therefore, in winter, the cavity will have a temperature similar to that of the indoor air and the building's transmission losses will decrease. Simulation results show that the heating demand is slightly higher when introducing natural ventilation (17.3 kWh/m^2) into the building compared to a fully air-conditioned mode (14.1 kWh/m^2). The Post Tower can be ranked second best with an energy consumption for heating of around 30.8 kWh/m^2. Waste heat from electricity production (district heating) is the energy source for heating. The deep cavity (120-170 cm) of the double-skin façade acts as a thermal buffer between the outdoor and the indoor air. On cold winter days, fresh air first is warmed up in the double-skin façade before it enters the perimeter fan coil units; thus, reducing the need for heating. The energy consumption for heating of the Commerzbank is 42.5 kWh/m^2, higher than of the Mary Axe and the Post Tower. Heating is provided by the local district heating network and is distributed through thermostatically operated radiators. The double-skin façade of this building has the narrowest cavity (20 cm) among the three buildings. However, window-to-wall ratio, which strongly influences the amount of solar heat gain versus the transmission losses through the envelope, is considerably lower in the Commerzbank (58%) than of the other sustainable cases (100%).

From the total energy use of the EWI building, more than half of it is consumed for heating. The heating source is a combination of local district heating (124.8 kWh/m^2) and a ground-coupled heat pump system (16 kWh/m^2). The double-skin façade with 95 cm cavity should act as a thermal buffer for office areas but the high amount of heating demand shows that this façade is underperforming. A poor performance single-glazed curtain wall with high infiltration and a cavity that is always vented with outside air (also in winter) are the reasons for high heating demand at the EWI building. Additionally, heating systems (hot-water radiators) are installed directly behind a single-glazed façade along the hallway which means a lot of heat loss through this thin layer of glass.

Ventilation

Interestingly, all selected sustainable buildings in the temperate climate, use both natural and mechanical ventilation. However, the duration and place of using natural ventilation varies depending on the design and the interior plan configuration. In

TOC

case of the Commerzbank, inward-facing offices that use tempered fresh air from sky gardens and the atrium can be naturally ventilated throughout the entire year; though, the outward-facing offices with direct access to fresh air can utilize natural ventilation for about 80% of the year (Jenkins, 2004). For the Post Tower, a combination of cross and stack ventilation provides all working areas and communal spaces with fresh air naturally. Only interior meeting rooms and conference halls are conditioned mechanically. Outside air enters the building through the double-skin façade, flows from the offices into the corridors and then is exhausted through the sky gardens. In addition, the outer skin of the façade is extended to create an aerodynamic form which increases the ventilation rate (Dassler et al., 2003). In both projects, the double-skin façade is naturally ventilated and night-time ventilation is applied during summer. The office areas in the Mary Axe building are not ventilated directly through the façade. Fresh air first comes into 6 peripheral atria through small openings in the façade before this tempered air is distributed to the working areas. For the original design, it was predicted that the office areas could be naturally ventilated without heating and cooling during 41-48% of the year. But with a change from owner occupation to multi-tenant occupation, most tenants rejected the energy-efficiency package with automated windows and choose for the year-round air conditioning package instead (Wood & Salib, 2013a). However, the central service core needs to be mechanically ventilated due to a deep plan (13.1 m from central core at middle floors). The cavity inside the facade is not ventilated with fresh air but with extracted air from the offices. Furthermore, the building does not use summer night-time ventilation.

The construction of the EWI building dates back to the 1960s when the development of double-skin façade technology was in its infancy. The air inlets for natural ventilation are placed in the middle of the façade but the air outlets are at the end of the facade. In summer, hot air in the cavity must run to the end of cavity to be exhausted. Therefore, ventilation in the cavity is hardly working even with the help of two exhaust fans inside the cavity. As a result, part of the heat is transferred from the cavity to the office spaces through a single-pane window increasing the cooling load of the building. Interior spaces are equipped with mechanical ventilation. Since, no separate ventilation is considered for corridors, part of the extracted air from the offices (30%) is transferred to temper the circulation areas while the rest is exhausted through the rooftop.

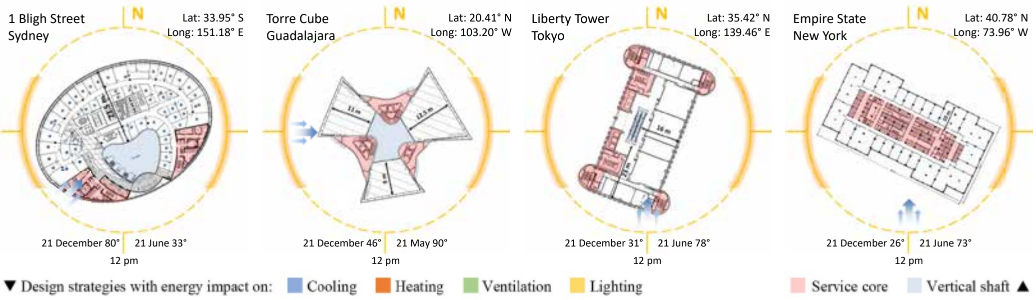
Lighting

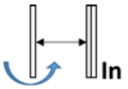
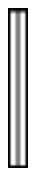
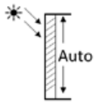
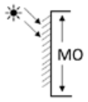
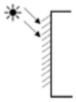
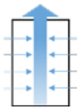
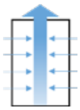
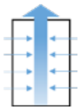
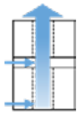
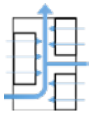
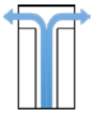
The Commerzbank has the highest building-related electricity consumption (67.7 kWh/m^2) among the cases in the temperate climate. As it is not clear how much of this energy is used for lighting (separate from pumps and fans), it is difficult to determine the causes for this: it might be a result of a prestigious design, higher number of occupants per square meter or architectural design features like window-to-wall ratio and plan depth. Considering the façade transparency, the Commerzbank has the lowest window-to-wall ratio of approximately 58%. This could mean that there is more need for artificial lighting. However, a full height central atrium and 9 spiral sky gardens bring a lot of natural light deep into the building interior. In the Post Tower, around 85% of the working stations are located within 5 meters from the external façade. Using daylight for the majority of office spaces resulted in a significant reduction of energy demand for artificial lighting. Additionally, most of the central meeting rooms and service spaces are faced toward a full-height atrium and can be naturally lit. The office spaces operate in stand-by mode when the rooms are empty. Of the total electricity consumption, lighting is 6.2 kWh/m^2 (Welfonder, 2006). In the Mary Axe building, the distance between the core and perimeter ranges from 6.4 to 13.1 m depending on the floor. This building thus has a deeper plan compared to the other cases. However, the problem of a deep plan is solved here with the help of 6 triangular atria along the building perimeter. The six rectangular office fingers can be naturally lit from three directions. The big central service core should always be artificially lit due to its central positioning. The total electricity consumption for lighting are respectively 26.4 and 29.1 kWh/m^2 for the mixed-mode (levels 2-15) and the fully mechanically conditioned (levels 16-34) zones (N. Clark 2014, pers. comm. 12 May).

The EWI building's electricity consumption for lighting, pumps and fans is around 46.4 kWh/m^2. Part of the cooling load is also combined with the electricity usage. Considering the educational function of this building with some labs and lecture halls, the energy use for lighting would be in an acceptable range (24.7 kWh/m^2). However, from the total floor area of this building, just the first three storeys are used for educational purposes while the upper floors are used as offices with cellular work areas. A narrow plan depth beside the peripheral arrangement of office spaces within six meters from the external façade are effective strategies for reducing the energy demand for lighting.

§ 2.4 Sub-tropical climate

A comparison of design strategies and energy consumption data for the case buildings in the sub-tropical climate are presented in Figure 2.4 and 2.5 respectively.



Energy impact	Strategies / Cases	Commerzbank	30 St. Mary Axe	Post Tower	EWI
🟦 🟧 🟩 🟨	Façade type				
🟦 🟨	Shading				None
🟩	NV type				SSV (limited)
🟦 🟩	Design strategies assisting in NV				None
🟦 🟧 🟨	Window-to-wall ratio	100%	35%	25%	20%

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TOC

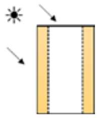
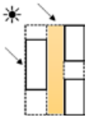
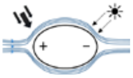
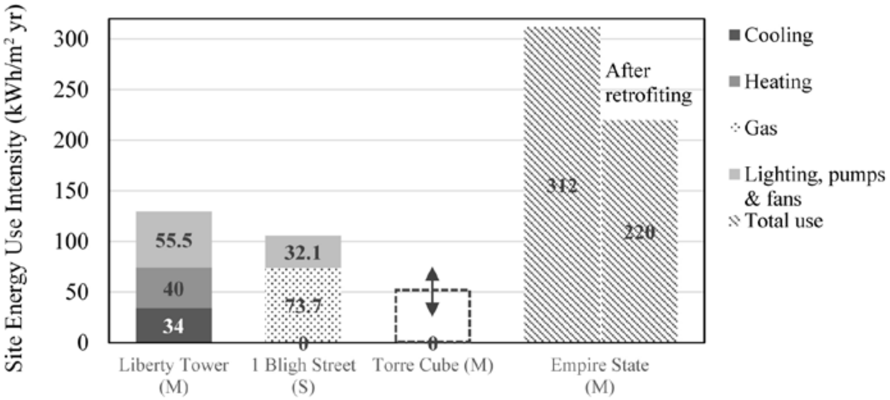
Energy impact				Strategies / Cases	Commerzbank	30 St. Mary Axe	Post Tower	EWI
			🟨	Design strategies assisting in daylight control			None	None
🟦		🟩	🟨	Service core placement				
🟦		🟩	🟨	Building form and orientation				
		🟩		Plan layout	Cellular	Open plan	Mixed	Mixed
		🟩	🟨	Plan depth	23.5 m from void	9–12.5 m from void	25 m from void	10 m from core
🟦	🟧	🟩	🟨	Control of indoor climate	BMS	Occupant	BMS	Occupant (limited)
🟦	🟧			Thermal buffer spaces	0.6 m DSF cavity	Peripheral multiple-cores	None	None
🟦		🟩		Summer nighttime NV	✗	✗	✓	✗
		🟩		Mixed-mode vent	✗	✗	✓	✗
🟦				Greenery system	✗	✗	✗	✗
🟦	🟧			Internal zones with different temp	✓	✗	✗	✗

FIGURE 2.4 A comparative study of design strategies for case buildings in the sub-tropical climate.



(S)=Simulated; (M)=Metered; the electricity consumption is just for lighting, pumps and fans. [1]The energy consumption of the Liberty Tower (Kato & Chikamoto, 2002) is converted from primary energy to delivered energy with an average efficiency factor around 45.4% for power plants in Japan. The conversion was calculated based on the average energy efficiency of power plants for electricity generation from local primary energy sources for the same year the Liberty tower's energy consumption was measured. [2]1 Bligh Street (Yudelson & Meyer, 2013) building use a tri-generation system for combined cooling, heating and electricity generation. The projected energy sources are gas and electricity. However, it is not clear how much is used to generate heat or lighting. [3]Torre Cube (Wood & Salib, 2013b) does not rely on an air-conditioning system for cooling, heating or ventilation. Therefore, the thermal energy consumption is zero in this building. The electricity consumption for lighting and equipment has not been published for this building. Therefore, the predicted consumption is presented with a dashed line. [4]The energy consumption data for the Empire State (Johnson Controls, 2013) is the total metered energy use before and after the retrofitting program.
Detailed information regarding the weather file, heating degree days (HDD) and cooling degree days (CDD) of each case study/city are presented in the table below.

CASE STUDY / CITY	LIBERTY TOWER / TOKYO	1 BLIGH STREET / SYDNEY	TORRE CUBE / GUADALAJARA	EMPIRE STATE / NEW YORK	
Year	2000	IWEC*	IWEC*	2007	2012
HDD	1417	580	534	2355	2286
CDD	1003	1000	1361	828	954

*IWEC: International Weather for Energy Calculation (US Department of Energy). *For energy simulations, a dynamic method based on hourly values was employed and the energy results were generated from IWEC weather data for each location. HDD and CDD data were obtained from BizEE Software Ltd.*

FIGURE 2.5 Energy performance data of the sub-tropical cases for one year.

Cooling

Among the cases from the sub-tropical climate, Torre Cube has the lowest energy consumption for heating and cooling (0 kWh/m^2) since it does not depend on an air-conditioning system. Due to the mild climate in Guadalajara, buildings in this city

TOC

can be naturally ventilated throughout almost the entire year if designed well. Solar radiation intensity, however, is very high making sun-shading an essential strategy to keep the building's cooling demand low. Adjustable external screens besides minimizing the proportion of window-to-wall ratio by around 35% are the two main strategies that protect this building from excessive heat gain in summer. The 1 Bligh Street building in Sydney is equipped with a hybrid tri-generation system that simultaneously generates heat, cold and electrical power. In this building, 500 m^2 of the roof is covered with solar collectors that feed the absorption chiller to generate cold (Lehmann & Ingenhoven, 2009). Therefore, the building does not use electricity from the grid for cooling. Furthermore, the compact elliptical form has 12% less surface area exposed to the outdoor climate than a rectilinear building of the same volume (Yeang, 2008) thus reducing the heat gains and losses through the building envelope. In addition, a high-performance naturally ventilated double-skin façade with 60 cm cavity helps to reduce the heat transfer through the envelope. However, there is some debate considering the land use and ecology of this building. The building's orientation and configuration of plan are mainly derived from the urban grid and the desire to maximize the view, not from environmental concerns. While the service core could have been used as solar buffer on the hot east and west sides, it is placed on the south side (non-harbour side of the floor plate). The Liberty Tower in Tokyo has a higher occupancy rate due to its educational function, thus a higher cooling demand compared to an equivalent office building. The building uses around 34 kWh/m^2 for cooling which is higher than the other two sustainable buildings. However, the 1 Bligh Street building's dependence on renewable energy (solar energy) for cooling does not mean that the cooling demand of this building is less than of Liberty Tower. This building does not seem to be oriented environmentally. The majority of lecture rooms are facing (south)east whereas the opposite (north)west contains the majority of service areas. Vertical and horizontal concrete fins on the façade protect the openings from high solar gains in summer.

In the sub-tropical climate, the Empire State building represents a traditional high-rise building design with a central service core that is fully air-conditioned and not oriented environmentally. Prior to refurbishment in 2009, the building's total energy consumption was 100 kWh/m^2 higher than the median energy consumption of office buildings in the US. However, an innovative energy-saving retrofitting program reduced the building's total energy consumption by 38% which also led the building to receive a gold certification under the LEED rating system for operation and maintenance in the year 2011. Some of the effective strategies for reducing the cooling load include improved insulation of existing windows (gas-filled and use of coated film), retrofitted chiller plants and replacement of old air handling units with fewer and more efficient units. Furthermore, providing tenants with access to online energy consumption and benchmarking information encourages them to be more energy conscious.

TOC

Heading

As mentioned before, Torre Cube has zero energy use for heating due to the mild weather conditions in Guadalajara. During the cold months (December and January) the daily mean temperature is around 17 °C (See appendix 1). This means that the internal and passive solar heat gains are sufficient to warm up the small interior office spaces. Liberty Tower's heating load is around 40 kWh/m^2. The rectilinear shape of this building increases the exposed surface area and therefore the heat losses through the envelope. Based on computer simulation analysis of the design proposal, the 1 Bligh Street building uses 73.7 kWh/m^2 of gas to feed a gas-fired tri-generation system which generates electricity and useful heat. This system is up to 50% more efficient compared to conventional grid-connected systems. From the waste heat, 'free' cooling and hot water can be generated. The office spaces are fully air-conditioned and separated from the atrium by glass walls. Extracted conditioned air from the offices is used to temper the naturally ventilated atrium. However, the building's energy use for heating, which is part of the 73.7 kWh/m^2, has not been published.

Also, the figures for the heating energy demand of the Empire State building are not published separately, but the total amount of energy consumption of this building is the highest among the sub-topical cases, even after the retrofitting program. This result emphasises the fact that the most effective strategies contributing to energy-saving of building design are those applied before construction.

Ventilation

1 Bligh Street has two separate ventilation strategies. The communal heart of the building is naturally ventilated but the working areas are fully mechanically ventilated. Natural fresh air is provided through an opening on the ground floor and a sky garden on the 15th floor and is distributed on all floors by stack ventilation in a full height atrium. The building is designed in a way that the perimeter cellular offices may potentially use single-sided natural ventilation if the interior glass panels are replaced with operable ones. But the deep floor plan does not allow for cross ventilation. This is an example of a building design on which changes in tenancy patterns and the consequent different space usage were accounted for in the design stages, in spite of the fact that it is just limited to the perimeter cellular offices. With the help of natural ventilation, the annual cooling demand of Liberty Tower was reduced by 17% (Kato & Chikamoto, 2002). Two architectural elements that effectively have improved this natural ventilation strategy are the escalator void and a wind floor on the 18th floor on top of the circulation shaft. CFD analysis has shown that the wind floor increases the air flow rate by 30% (Chikamoto et al., 1999). As the escalator void is not segmented,

there is a risk of an extreme stack effect and draft inside the building. Furthermore, the introduction of fresh air directly into the working areas might provide discomfort especially for the occupants sitting near the air inlets. In the Liberty Tower, cool fresh air comes in directly through the inlets below the fixed windows. The inability of the occupants to control their operation (fully controlled by a BMS) may limit their comfort and may result in user dissatisfaction (cold feet) (Wood & Salib, 2013c). The Torre Cube building uses different architectural elements to provide both cross and stack ventilation. Fan-shaped office wings help to funnel the air across the working spaces before it is exhausted through a central open void. Three open spiral sky gardens lead to a higher air circulation in the void. However, without a CFD analysis it is not clear if the sky gardens have a positive or a negative effect on buoyancy in the central void.

Similar to other traditional high-rises, the Empire State building is fully dependent on mechanical ventilation with no air inlets or operable windows for introducing natural ventilation into the building. However, after the retrofitting program the building was equipped with CO_2 sensors for the control of the ventilation demand.

Lighting

1 Bligh Street has a fully transparent façade. Due to a deep plan (23.5 m from façade to central void), there are three working zones between the building perimeter and the atrium which means just 30% of permanent working stations are within 5 meters of this façade. A central atrium and transparent partitions are used to increase natural light penetration. Temporarily used spaces like meeting rooms are placed in the mid-zone. The figures of electricity consumption for lighting, fans and ventilation are not available separately but the total delivered electricity is around 32.1 kWh/m^2. Torre Cube's electricity use for lighting has not been published. Because of a central void, the office wings in this building receive daylight from two sides, which allows for a deep office plan of about 9-12.5m. The electricity use for lighting and pumps of Liberty Tower is around 55.5 kWh/m^2. In comparison with 1 Bligh Street, the Liberty Tower and Torre Cube have considerably lower window-to-wall ratio of around 25% and 35% respectively.

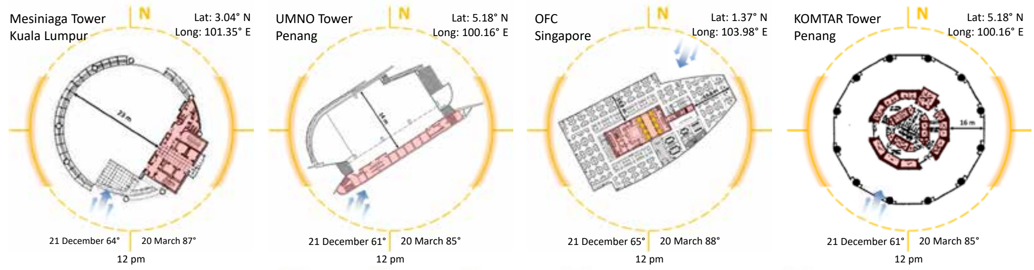
The construction of Empire State building dates back to 1931 when high-rise building design was mostly affected by the 1916 zoning law (typical wedding cake buildings with series of setbacks) and prior to the development of the glazed curtain walls in 1951 (Oldfield et al., 2008). Therefore, façade transparency is lower (WWR: 20%) as compared to the other cases in the sub-tropical climate. However, due to the New York zoning law (1916), no office space is deeper than 8.5 meter; thus, the slender shape of this building provided greater natural light penetration compared to the compact pre-

TOC

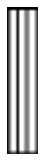
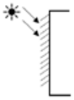
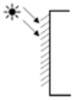
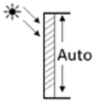
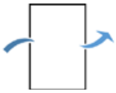
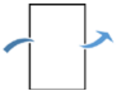
zoning law buildings. Outfitting offices with occupancy sensors, better lighting controls, and layouts that maximize natural daylight were part of the retrofitting program for improving the energy-efficiency.

§ 2.5 Tropical climate

A comparison of design strategies and energy consumption data for the case buildings in the tropical climate are presented in Figure 2.6 and 2.7 respectively.



▼ Design strategies with energy impact on: 🟦 Cooling 🟧 Heating 🟩 Ventilation 🟨 Lighting 🟥 Service core ⬜ Vertical shaft ▲

Energy impact				Strategies / Cases	Mesiniaga	UMNO	OFC	KOMTAR
🟦		🟩	🟨	Façade type				
🟦			🟨	Shading				None
		🟩		NV type			None	SSV (limited)

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TOC

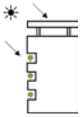
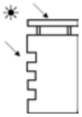
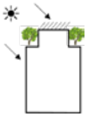
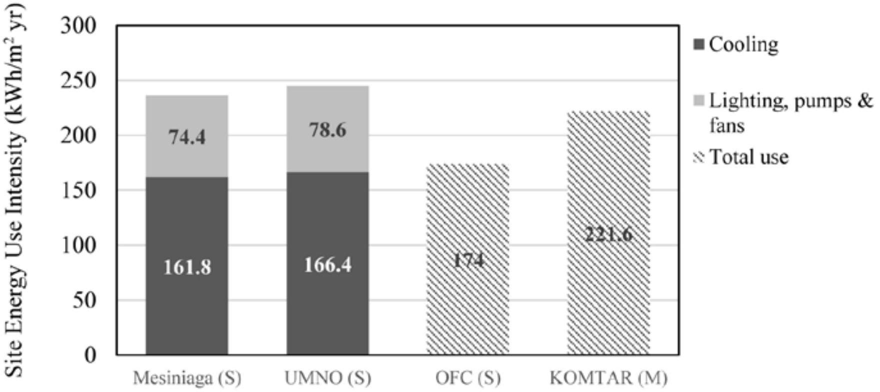
Energy impact				Strategies / Cases	Mesiniaga	UMNO	OFC	KOMTAR
🟦		🟩		Design strategies assisting in NV	None		None	None
🟦				Window-to-wall ratio	65%	60%	100%	80%
🟦			🟨	Design strategies assisting in day-light control				None
🟦		🟩	🟨	Service core placement				
🟦		🟩	🟨	Building form and orientation				
		🟩	🟨	Plan layout	Open plan	Open plan	Open plan	Mixed
		🟩	🟨	Plan depth	23 m from core	14 m from core	13.8–19.8 m from core	16 m from core
🟦		🟩	🟨	Control of indoor climate	Occupant	Occupant	BMS	Occupant (limited)
🟦				Thermal buffer spaces	Service core (east side)	Service core (east side)	None	None
🟦		🟩		Summer night-time NV	✗	✗	✗	✗
		🟩		Mixed-mode vent	✗	✗	✗	✗
🟦				Greenery system	GB	✗	SG	✗
🟦				Internal zones with different temp	✓	✓	✗	✗

FIGURE 2.6 A comparative study of design strategies for case buildings in the tropical climate.



(S)=Simulated; (M)=Metered; the electricity consumption is the total usage for lighting, pumps and fans. [1]The yearly electricity consumption for the Mesiniaga Tower (Jahnkassim, 2004), the UMNO Tower (Jahnkassim, 2004) and the OFC (Keppel Land, 2011) are simulated energy - all the three cases were employed a dynamic method based on hourly values - but for the KOMTAR Tower (Ismail, 2007) is metered energy.
Detailed information regarding the weather file, heating degree days (HDD) and cooling degree days (CDD) of each case study/city are presented in the table below.

CASE STUDY / CITY	MESINIAGA / KUALA LUMPUR	UMNO / GEORGE TOWN	OFC / SINGAPORE	KOMTAR / GEORGE TOWN
Year	IWEC*	IWEC*	IWEC*	2004
HDD	0	0	0	0
CDD	3730	3690	3730	3727

*IWEC: International Weather for Energy Calculation (US Department of Energy). *For energy simulations, a dynamic method based on hourly values was employed and the energy results were generated from IWEC weather data for each location. HDD and CDD data were obtained from BizEE Software Ltd.*

FIGURE 2.7 Energy performance data of the tropical cases for one year.

Cooling

In a tropical climate, cooling and lighting are the two largest contributors to the total energy use for an office building. For the Ocean Financial Centre (OFC), cooling is provided by a hybrid chilled water supply and the district cooling system. The building's external shell is entirely covered by a triple-glazed glass facade with low-e coating and solar control film. Automatically adjusted indoor blinds let the natural light come in but prevent unpleasant glare. As a result, the transmission gains through the envelope of OFC are 15% less (Keppel Land, 2011) compared to a standard value for the same location (50 W/m^2). However, even a very high-performance glazing still allows about one-third of the sun's heat to enter the building. Therefore, a fully glazed façade might increase the cooling demand. The building's form and orientation are suboptimal from an energy-efficiency perspective since they were derived solely from the city grid and the aim to maximize the view to the harbour. The central positioning of the service core and the use of the hot sides of the building as permanent work areas leads to an extra energy demand for cooling. The energy consumption for cooling is not published separately, however the total energy consumption is less than of the other cases in the tropical climate.

Simulations showed that the energy consumption for cooling of the Mesiniaga Tower is around 161.8 kWh/m^2. The building's circular shape allows for the smallest surface exposure to the outdoor climate (25% less compared to a rectilinear form with the same volume) (Yeang, 2008); therefore, lower thermal transfer through the envelope. External shading along the perimeter (with higher coverage on the west side) and the placement of the service core approximately towards east are two important strategies for reducing the solar heat gains on the hot sides of this building. Recessed terraces are another strategy for providing deep permanent shading. Buffer spaces, such as service areas placed along the perimeter of the building, could reduce the amount of glazing thus reducing solar heat gains. Additionally, such placement provides the possibility of using natural ventilation and daylight in these service areas. In the tropics, surface to volume ratio is an important factor which determines the amount of external heat gains. Therefore, it is important to find a balance between the shading by recessed balconies and the increased external envelope surface. Balconies should be placed such that they cut off direct radiation during the hot hours of the day. Otherwise the effect of heat transfer through the increased surface will offset the shading effect by recessed terraces. Random placement of balconies similar to the spiral recessed terraces of the Mesiniaga Tower, could increase the energy demand in comparison with the simple cylindrical model for this building. According to simulations by Johnkassim & Ip (2006), a slight reduction of the cooling demand (1-2%) was observed for the compact cylindrical form without spiral balconies.

The UMNO Tower can be ranked third with an energy consumption for cooling of around 166.4 kWh/m^2 slightly higher than of the Mesiniaga Tower. For the original design, a natural ventilation strategy for the full year was proposed with a provision for tenants to install AHUs. However, after the construction, natural ventilation was applied only to the circulation area and the lift lobbies. Partition walls between the spaces were added and a floor-by-floor basis air-conditioning system was installed. Due to site limitations, the building could not be oriented to the direction of the prevailing wind. As a result of that, two wind wing walls were developed to catch and lead the wind into the building. The location of the service core with a thick concrete wall along the south-east façade allows to act as a thermal buffer on the hot side and reduces the cooling load significantly by 12%. Multiple balconies on the west side help to cut off direct radiation at critical hot hours with a positive impact on cooling reduction by about 4% in the UMNO (Johnkassim & Ip, 2006). External shading screens are more closed towards the west and more transparent towards the north. The rooftop is also covered by a large curved canopy which blocks the roof from direct solar radiation.

The KOMTAR Tower is an example of a typical high-rise building that is fully air-conditioned, that has a facade almost completely covered with full height single layer glass and has a central service core. The floor plan of the building is a 12-sided polygon and is identical on all sides. The window to wall ratio is around 80% while there is no external shading device or recessed terrace to shade the facade. However, the building is equipped with manually controlled indoor blinds that also block the view. Surprisingly, the metered energy data for this building shows a different trend. The cooling load is not available separately but the total energy use of the KOMTAR Tower is less than of both Mesiniaga and the UMNO Tower, two of the sustainable high-rises. One reason could be that the KOMTAR's reputation is currently dropping as a result of poor maintenance and lack of facilities in competition with fancier modern buildings in its vicinity. Therefore, the KOMTAR tower has a few unoccupied floors and that for calculating the EUI these floors are included. Whereas the other two sustainable buildings are fully occupied.

Heating

In equatorial areas, the average annual temperature is almost constant throughout the year around 30 °C, which means there is no need for heating.

Ventilation

The office areas in the Mesiniaga Tower are mostly air-conditioned and only the service core is naturally ventilated. Since the natural ventilation strategy mainly relies on cross-ventilation, it is difficult to provide an acceptable air flow rate along the plan (30 m plan diameter). However, the use of two wind wing walls at UMNO Tower, resulted in a higher indoor air flow rate in this building and a wider range of wind directions being captured. Similar to the Mesiniaga Tower, in the UMNO building, the service area is naturally ventilated but the office areas are mostly mechanically ventilated. In both projects there is no BMS to control the operation of openings. Therefore, it might cause problems in attaining the required airflow rate needed for ventilation especially in this humid tropical climate. KOMTAR and OFC are both fully mechanically ventilated except for two mechanical floors in OFC that have air inlets for natural ventilation. Furthermore, the service core in this building also do not have this potential to be naturally ventilated due to its central positioning.

TOC

Lighting

The OFC has the highest façade transparency among the four cases studied in the tropical climate. The rooftop is equipped with 400 m^2 of PV cells which not only shade the roof and provide a communal space but also produce enough renewable energy to provide electricity for lighting more than 4,500 m^2 of office space. The energy consumption for lighting has not been published but the total energy use is 174 kWh/m^2. The building is equipped with energy-saving technologies such as high-efficiency lighting and motion sensors for all of the working stations and service areas, and a regenerative drive lift system that has 75% higher efficiency compared to conventional lifts. However, a deep plan which exceeds to more than 20 m in some floors resulted in a higher demand for artificial lighting specifically for the central service core.

Although the total energy consumption of the Mesiniaga Tower is lower than of the UMNO Tower, the electricity usage is slightly higher. The reason can be due to a deeper plan of Mesiniaga (23 m) compared to UMNO (14 m). In both of the projects the façade transparency is around 80% on all sides except east (Ismail, 2007) and the service core is positioned on the southeast side. Spiral recessed terraces in Mesiniaga bring daylight deeper into the plan which can ameliorate the negative effect of the deep plan.

Considering European standards for office buildings, permanent working areas should not be located farther than 8 m from the facade. Although the plan depth of KOMTAR is 16 m from façade to central core the illuminance level in the offices is measured to be 4 times higher than recommended and is between 4000-4500 lux (Fairuz Syed Fadzil & Sia, 2004). Furthermore, the central service core increases the energy demand for artificial lighting.

§ 2.6 Lessons learned: Effective design strategies for high-rises

This section provides design recommendations for reducing the energy consumption of high-rise office buildings in temperate, sub-tropical and tropical climates. These recommendations are based on a combination of literature review on passive design techniques and the lessons learned from the analysis of high-performance design references.

§ 2.6.1 General design strategies for high-rise office buildings

Concerning plan configuration, it is important to place the permanent work stations close to the envelope to reduce the need for artificial lighting. Dividing the internal zone into areas with different temperature is another important strategy that can reduce the cooling/heating load of high-rise buildings. Office workers expect a high degree of comfort in their work stations but tolerate a little bit of discomfort in lift lobbies and communal spaces.

Plan form and building shape (or compactness) can influence the amount of heat gain or loss through the envelope. Circular and elliptical forms have an exposed surface area that is respectively 25% and 12% less than of a rectilinear building of the same volume. Furthermore, an aerodynamically curved form minimizes wind turbulence and downdraft at street level.

Furthermore, the effectiveness of natural ventilation and daylight depends strongly on how the openings and solar shading devices are controlled. The absence of a central BMS might cause problems in attaining the right adjustments for providing indoor comfort conditions and may increase the energy consumption. Smart occupancy sensors cut down unnecessary consumption for lighting, and mechanical ventilation. In cellular offices, it is important that occupants can override the BMS to ensure their individual comfort. Psychologically, occupants with more control over their environment are more tolerant to high or low temperatures. However, the BMS should automatically switch off the air-conditioning system if occupants decide to open the window.

§ 2.6.2 Design strategies for high-rise office buildings in a temperate climate

Façade transparency and plan depth are the two dominant factors with great influence on the electricity demand for lighting. A fully transparent façade is a common strategy in a temperate climate. However, it is important to provide a balance between the use of daylight, the solar heat gain in summer and the heat loss in winter. A double-skin façade with a deep cavity is an effective strategy for reducing the cooling and heating loads of high-rise buildings in temperate climates. A double-skin façade can act as a thermal buffer between the outdoor and indoor environment. The deep cavity ensures that in summer solar radiation does not enter the office spaces. Moreover, offices next to this façade can use natural ventilation for a longer period of time if fresh air first passes through the cavity in the double-skin façade before entering the offices. However, an effective ventilation strategy is highly needed inside this cavity especially during summer; otherwise the double-skin façade would act like a greenhouse and transfer a lot of heat into the building. Solar control devices within the cavity, like motorized venetian blinds, allow for passive heating in winter but prevent unpleasant glare and overheating in summer.

A mixed-mode (natural and mechanical) ventilation strategy can reduce effectively the energy demand for cooling and mechanical ventilation. Some architectural elements that can help the air intake, circulation and exhaust are sky gardens and vertical shafts like atria and circulation voids. When using a full-height atrium, there is a risk of high temperature differences and extreme stack effects and drafts. For controlling this excessive stack effect, a full-height atrium is usually segmented into smaller zones with lower pressure difference.

§ 2.6.3 Design strategies for high-rise office buildings in a sub-tropical climate

In a sub-tropical climate, solar radiation intensity is high. Therefore, the most effective design strategies are those that reduce the solar heat gain. Such strategies include limited façade transparency on the east and west side of the building, the placement of service cores on the hot sides (double-sided core on east and west) and the extensive use of shading devices. Glazing type is usually double-glazing with low-e coating.

Placing the work stations along the north and south façade is a good strategy for reducing the electricity demand for artificial lighting. However, the size and position of openings should protect the occupants form direct solar radiation and glare. Using external shading and indoor blinds improves the quality of daylighting.

Similar to a temperate climate, natural ventilation is also an effective solution for reducing the cooling demand in a sub-tropical climate. However, introducing humid outdoor air may reduce thermal comfort of the occupants as a result of which constant humidity control is an essential element of such a strategy.

§ 2.6.4 Design strategies for high-rise office buildings in a tropical climate

Intense radiation, high humidity, low wind speeds and a constant high air temperature throughout the year are significant climatic features in the tropics. The best energy-saving strategies for reducing the cooling load are those that limit heat gains. Shading the envelope (external devices or application of greenery systems), placing service areas as a thermal buffer on the hot sides with limited openings, using reflective external materials and finally minimizing surface to volume ratio are some of the strategies to control the heat gain. Shadings should be more obstructing towards the hot sides and more transparent on the other sides. Due to the high sun angle in these areas, it is also important to shade the roof and utilize energy generation systems like solar collectors or PV panels to compensate for the excessive cooling demand.

Multiple recessed terraces in the tropics act like sky gardens in a temperate climate. They are incorporated into the building design to provide solar shading and a communal space where occupants can enjoy the cool breeze. They also provide the possibility of making full height openings for bringing daylight deeper into the plan while shading the openings entirely. Moreover, they act as buffers with adjustable windows to control the rate and distribution of natural ventilation. In case of using recessed terraces, it is better to place them in directions that receive the highest radiation to limit heat gain during critical hot hours.

Natural ventilation can be utilized as an effective backup system in communal spaces and service areas but rarely for permanent working stations that seek higher comfort conditions. Due to low wind speeds, the application of architectural elements, such as wind wing walls, voids or an aerodynamic building form, is necessary to increase the air flow rate inside the building.

§ 2.7 Comparison with energy benchmarks

The total energy use of twelve case studies and related energy benchmarks in each climate/context are presented in Figure 2.8. Considering the energy standards in Germany & the UK for a naturally ventilated and heated building (123-135 kWh/m^2), the EUI of two cases in a temperate climate, 30 St Mary Axe and the Post Tower, are below the local benchmarks. The total energy consumption of the Commerzbank is around 140 kWh/m^2 which is slightly higher than the UK & German standards for

TOC

a naturally ventilated building. As a reference for typical high-rise design, the energy consumption at the EWI building is more than sustainable case buildings in temperate climate. However, the total energy use is below the standards for a mechanically ventilated building in Germany. This relatively lower energy consumption results from special design strategies such as a narrow plan and a supplementary ground-coupled heat pump system for heating and cooling.

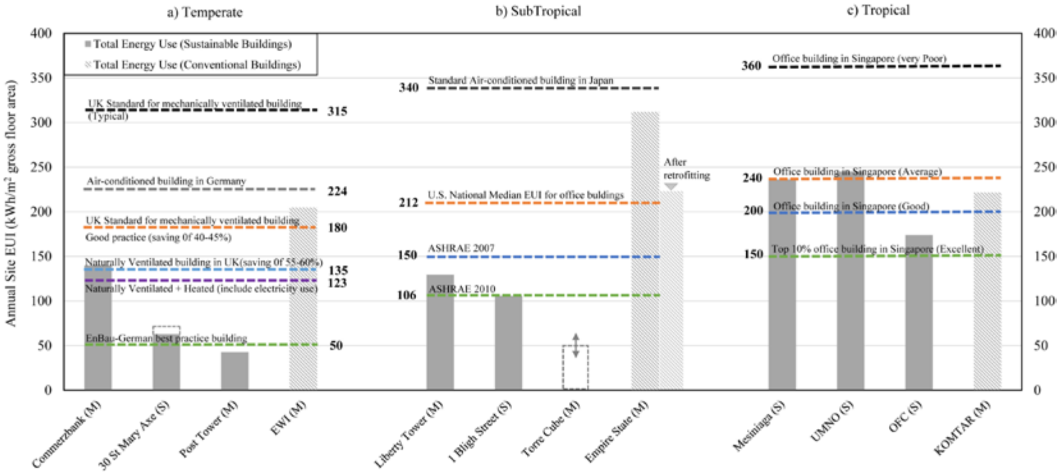


FIGURE 2.8 Comparison of building's energy performance with energy benchmarks in each climate/context. *(S)=Simulated; (M)=Metered; the electricity consumption is the total usage for lighting, pumps and fans. The electricity consumption for lighting pumps and fans has not been published for the Torre Cube. Therefore, the predicted consumption is presented with a dashed line. Energy benchmarks vary with country and source. German benchmarks use net area while UK benchmarks use gross area. In this graph, German energy benchmarks are normalized from net area to gross area with an average space efficiency factor around 65%. The EnBau standard is based on primary energy, therefore the site energy should be even less than the presented figure.*

In the sub-tropical climate, all of the three sustainable cases, have a lower energy consumption than the U.S. National Median of energy use for office buildings and ASHRAE 2007. Moreover, 1 Bligh Street and Torre Cube outperform ASHRAE 2010, with an energy consumption lower than 106 kWh/m^2. Torre Cube has the highest energy-efficiency with no dependence on cooling or heating systems that is to a large extent related to the mild weather conditions and the relatively low height. The Empire State building is an example of a typical high-rise building with high dependence on air-conditioning systems. Before 2009, the total energy use of the Empire State building was 100 kWh/m^2 higher than the US building's average energy use (212 kWh/m^2). Since 2009, the Empire State building has been retrofitted as such reducing the building's total energy consumption by 38%.

In the tropical climate, two cases are certified as sustainable, but their energy consumption exceeds the average for office buildings in Singapore. OFC is the only sustainable building that outperforms the energy benchmark for good practice office buildings. Although the KOMTAR building is a typical air-conditioned high-rise building with no sustainable design measures, the energy performance of this building is better than the Mesiniaga and the UMNO Tower. However, it should be considered that the KOMTAR Tower is an outdated building that has some floors unoccupied whereas the other two buildings are fully occupied.

§ 2.8 Discussion of comfort standards

There is no doubt that in some climates, buildings require heating and/or cooling to remain comfortably habitable. The indoor air temperature that is set for a building is a key factor in determining the energy consumption and thermal comfort. Standards, guidelines and legislations for the indoor comfort aim at improving the health and comfort of building occupants while reducing the energy use. ISO 7730 (2005), ASHREA 55 (2010) and European standard EN15251 (2007) are the three widely used international standards which address the indoor environment and thermal comfort (Nicol et al., 2012). Predicting the indoor air temperature at which people feel comfortable is a complex task that depends on several parameters including environmental, cultural and personal factors. The results of field surveys of different buildings and climates showed that the range of the comfort temperature for the people who work in a naturally ventilated building is different in comparison with an air-conditioned one. For this purpose, international standards use different prediction models to specify the comfort temperature boundaries within buildings. The international comfort standards use the predicted mean vote (PMV) index for mechanically conditioned buildings and the adaptive thermal model for naturally conditioned buildings to define acceptable indoor environments. The idea behind the adaptive comfort model is that the occupants of naturally ventilated buildings have a greater degree of control over their environment; therefore, thermal comfort ranges can be extended beyond the normal range.

In naturally ventilated buildings, the occupants' perception of indoor thermal comfort depends largely on outdoor air temperature variations. A comparison of mean monthly outdoor dry-bulb temperature (DBT) with indoor comfort temperature values for buildings in different climates is presented in Figure 2.9. In Figure 2.10, the energy use intensity of case studies along with the number of degree days for heating and cooling of each city/climate are provided. Comfort temperatures based on adaptive versus predicted mean vote (PMV) models are obtained from Climate Consultant version 5.4 for different locations. These figures represent 90% acceptability limits of the occupants. The adaptive comfort model and the PMV model are both defined in ASHRAE standard 55. The optimal temperature for comfort (T_{comf}) and the range of acceptable comfort temperatures (T_{accept}) based on the adaptive model are obtained by the following equations.

$$T_{comf} = 0.31T_o + 17.8\ °C$$

$$T_{accept} = T_{comf} \pm T_{lim}$$

In 2004, ASHRAE Standard 55 defined T_o initially as the mean monthly outdoor air temperature and later in the revised version of 2010 as the prevailing mean outdoor air temperature. Therefore, different forms of running mean temperature existed and the exact choice of the adequate form is left to the user according to the latest version of the standard (Nicol et al., 2012). Since the comfort temperatures in this paper are obtained by Climate Consultant version 5.4 and this version of software is programmed according to the ASHRAE Standard 55-2004, T_o represent here the mean monthly outdoor temperature. T_{lim} is defined as the range of acceptable temperatures. When a higher standard of thermal comfort is desired (90% of the occupants being satisfies), the given limits of acceptable comfort temperature is ±2.5K. This equation cannot be used when T_o is less than 10 °C or greater than 33.5 °C. Furthermore, this model does not apply when a mechanical cooling system is available or a heating system is in operation. However mechanical ventilation with unconditioned air may be utilised; thought the thermal comfort should be mainly provided by natural ventilation through operable windows. In Figure 2.9, the adaptive model presented minimum and maximum comfort temperatures for different locations. The lowest value is based on the coldest month that still has a mean monthly outdoor air temperature above 10 °C and that the highest value is based on the warmest month that still has a mean monthly outdoor air temperature below 33.5 °C.

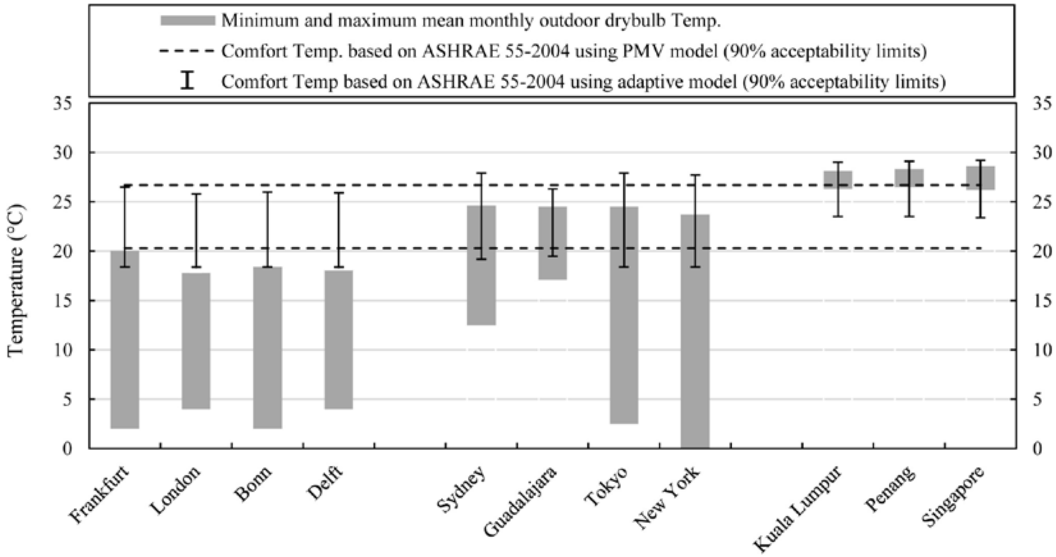


FIGURE 2.9 A comparison of mean monthly outdoor air temperature with comfort temperatures based on adaptive versus PMV models, respectively for buildings with natural ventilation and air-conditioning systems.

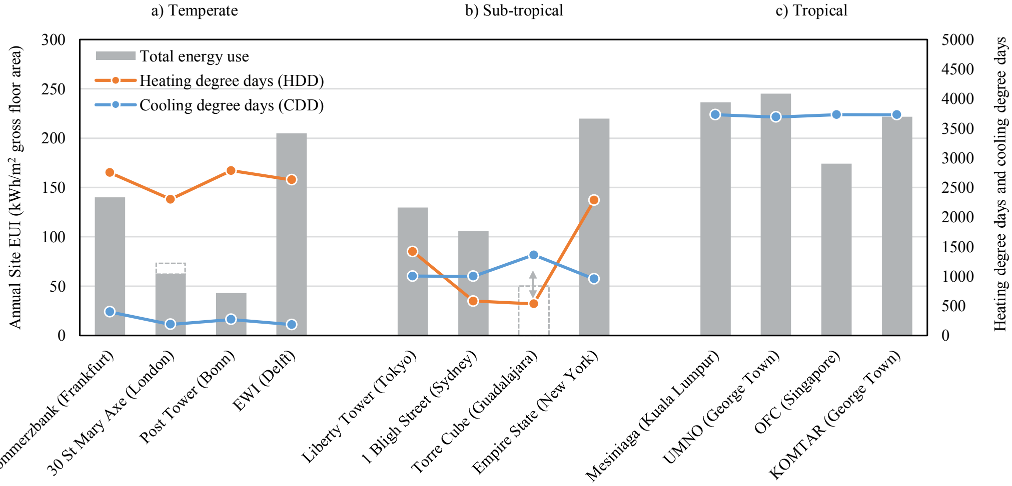


FIGURE 2.10 The energy use intensity of case studies along with heating degree days (HDD) and cooling degree days (CDD) of each city for the same year the energy data were collected.

In a temperate climate, minimum mean monthly temperature for all cases is far beyond the comfort bandwidths, which means heating is the main requirement in this climate. During the summer months, the maximum mean monthly temperature is almost in the same level as the lower limit of comfort temperature. The result of a post occupancy evaluation for Commerzbank (Frankfurt) showed that natural ventilation is possible up to 80% of the year for office spaces. This is a good example of how architectural design elements such as an atrium, sky gardens and a DSF with operable windows can extend the use of natural ventilation. Furthermore, occupants can override the BMS to provide their individual comfort in cellular offices. If occupants decide to open the window, the BMS will automatically switch off the air-conditioning system.

According to the Köppen-Geiger climate classification system (Peel et al., 2007), Sydney, Guadalajara, Tokyo and New York are all classified in the same climate category of sub-tropical. This climate type covers a broad range of features, especially in terms of winter temperatures. However, the solar radiation intensity and the summer temperature are relatively equal for all of the four cases in the sub-tropical climate. The higher energy consumption for heating in the Liberty tower (Tokyo) and the Empire State (New York) is partly explained because of a lower outdoor air temperature in winter compared to Sydney and Guadalajara. Furthermore, as it can be seen in the case of Guadalajara, more than 70% of the year the outdoor air temperature is within the comfort zone, which makes it easier to provide indoor thermal comfort by natural ventilation with no dependence on air-conditioning.

The adaptive thermal comfort model for the tropical climate shows that all cases are within the comfort zone if adequately being naturally ventilated. For naturally ventilated buildings, the availability of control over the indoor environment by the occupants, the cooling effects due to the elevated indoor air velocities and dehumidification of fresh air are some of the factors that can influence the occupants' thermal perception in tropical climates. However, it is important to mention that the solar heat gains and internal heat production can increase the indoor air temperature significantly as a result of which natural ventilation might not be enough and active cooling is required. According to the PMV model, people who are working in air-conditioned spaces would have higher expectations for indoor comfort; hence, have lower tolerance of temperature variations.

§ 2.9 Conclusion

Design strategies for tall office buildings were investigated through a comparative study of twelve high-rises in a temperate, a sub-tropical and a tropical climate. In temperate and sub-tropical climates, sustainable design strategies for high-rise buildings lead to lower energy consumption for cooling, heating, ventilation and lighting. In tropical climates, while some strategies might help to improve user's satisfaction, they can increase the energy consumption if not placed correctly. This means that sometimes a compact building may perform better than a 'perforated' one. Additionally, this research showed which design strategies are most effective for sustainable high-rises to reduce the energy consumption for cooling, heating, ventilation and lighting in three climates.

A mixed-mode ventilation strategy can effectively reduce the energy consumption for cooling also fans in temperate and sub-tropical climates. The effectiveness of natural ventilation can be improved by using special design elements like atrium (central or peripheral) and indoor sky garden, which can also bring daylight deeper into the plan. A fully glazed double-skin façade with automated blinds, operable windows and ventilated cavity is a common façade type among sustainable cases in temperate climate. In climates with higher solar radiation intensity, shading the envelope (e.g. green balconies and sky gardens), placing service areas as a thermal buffer on the hot sides with limited openings and finally minimizing surface to volume ratio are some of the strategies to control the heat gain; hence reducing the cooling demand. Moreover, placing the service core along the façade provide this possibility to be naturally ventilated and lit. Furthermore, the results showed that for tropics there is a need for higher concerns over the design of high-rise buildings since the energy consumption for sustainable buildings is relatively high in comparison with the energy benchmarks for a good practice building.

Acknowledgments

We thank the architects and engineers who responded with case-study information specifically Mr. Nigel Clark, the technical director of HilsonMoran Company by providing detailed operation data of the Mary Axe building.

Appendix 1

Climate data and locations of the selected case studies.

	Average daytime temperature during the hottest months (°C)	Average daytime temperature during the coldest months (°C)	Mean annual temperature (°C)	Average wind speed (m/s)	Global Horiz radiation in summer (Wh/m²)	Global Horiz radiation in winter (Wh/m²)	Average annual RH in summer	Average annual RH in winter
Frankfurt (Commerzbank)	24	4	10	4	4920	626.6	53%	76%
London (Mary Axe)				3.6	4945	742	66%	81%
Bonn (Post Tower)	17.4	3	9.6	3.1	4679	713	72%	83%
Delft (EWI)			10	5.4	4642	821	79%	88%
Sydney (1 Bligh Street)	26	17	18	3.8	6319	2465	66%	62%
Guadalajara (Torre Cube)					5654	3885	52%	60%
Tokyo (Liberty Tower)	29	11	16.1	1.9	4448	2586	72%	50%
New York (Empire State)					5258	1439	69%	63%
Kuala Lumpur (Mesiniaga)	32	31	28	1	4522	4069	80%	83%
Penang (UMNO) (KOMTAR)			27	1.3	5362	4399	81%	82%
Singapore (OFC)	32	29.5	27.5	1.6	4921	4296	85%	82%

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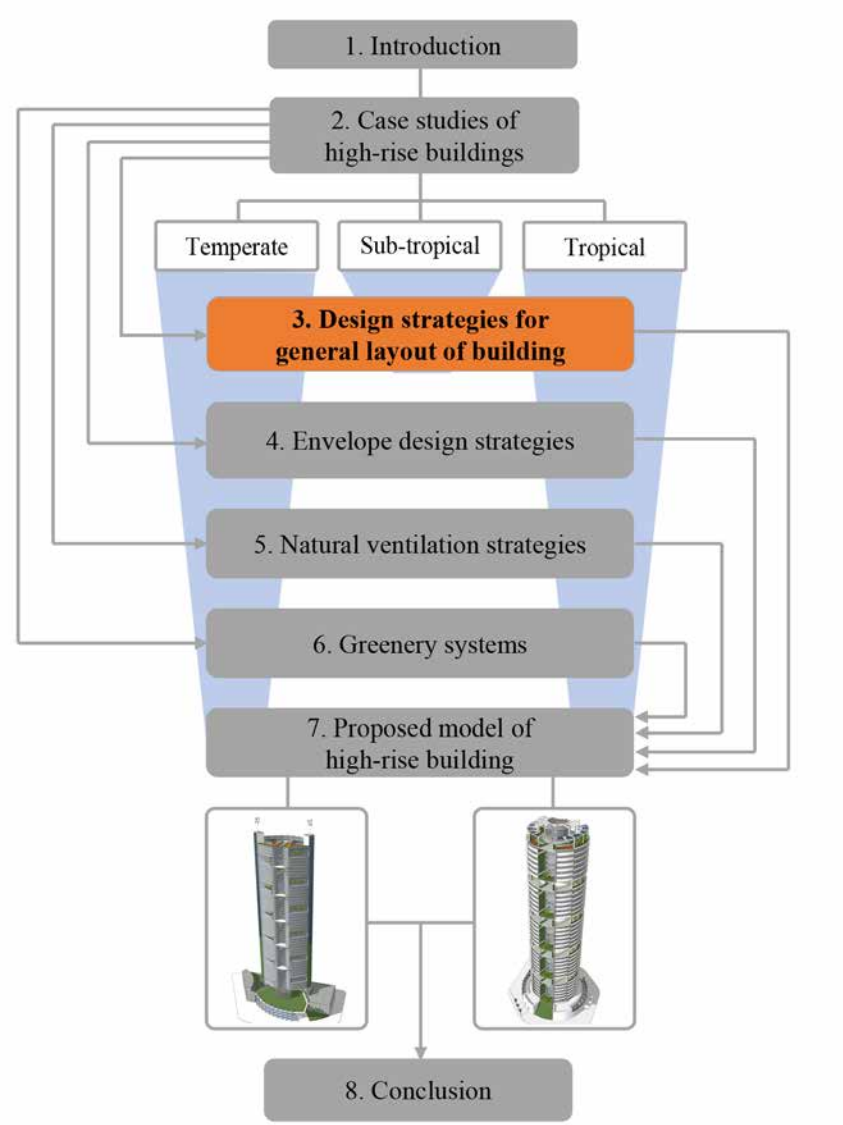
1. Introduction
2. Case studies of high-rise buildings
Temperate
Sub-tropical
Tropical
3. Design strategies for general layout of building
4. Envelope design strategies
5. Natural ventilation strategies
6. Greenery systems
7. Proposed model of high-rise building
8. Conclusion

TOC

3 Early-stage design strategies

On the basis of a case-study approach with multiple cases, chapter 2 compared the differences between twelve examples of high-performance (sustainable) and low-performance (conventional) tall buildings concerning the use of architectural design strategies and the energy usage patterns in three climates: temperate, sub-tropical and tropical. Certain architectural design strategies were found to be more common among sustainable buildings in each climate and had greater impact on the building performance and the quality of the indoor environment. These can be classified under the categories of geometric factors, envelope strategies, natural ventilation strategies, and greenery systems. To quantify the extent to which these architectural design strategies affect energy use and thermal comfort of tall office buildings, simulation studies should be carried out.

Chapter 3 focuses on the first group of design strategies, the geometric factors. It starts with a brief introduction and an overview of previous studies. Next, the incorporated building models for performing energy simulations, the results of a sensitivity test for determining simulation inputs and the climatic data of the selected locations are thoroughly described in section 3.3. The suitability of different plan shapes, plan depths, orientations and window-to-wall ratios for the energy-efficiency of tall buildings are discussed in section 3.4 for each of the investigated climates. The limitations of this study along with recommendations for the proper use of the findings is presented in section 3.5. At the end of this chapter, the impact of geometric factors on the energy-efficiency of high-rise office buildings in the three climates is concluded in a table.

TOC

Early-stage design considerations for the energy-efficiency of high-rise office buildings[2]

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Abstract:

Decisions made at early stages of the design are of the utmost importance for the energy-efficiency of buildings. Wrong decisions and design failures related to a building's general layout, shape, façade transparency or orientation can increase the operational energy tremendously. These failures can be avoided in advance through simple changes in the design. Using extensive parametric energy simulations by DesignBuilder, this paper investigates the impact of geometric factors for the energy-efficiency of high-rise office buildings in three climates contexts: Amsterdam (Temperate), Sydney (Sub-tropical) and Singapore (Tropical). The investigation is carried out on 12 plan shapes, 7 plan depths, 4 building orientations and discrete values for window-to-wall ratio. Among selected options, each sub-section determines the most efficient solution for different design measures and climates. The optimal design solution is the one that minimizes, on an annual basis, the sum of the energy use for heating, cooling, electric lighting and fans. The results indicate that, the general building design is an important issue to consider for high-rise buildings: they can influence the energy use up to 32%. For most of the geometric factors, the greatest difference between the optimal and the worst solution occurs in the sub-tropical climate, while the tropical climate is the one that shows the smallest difference. In case of the plan depth, special attention should be paid in a temperate climate, as the total energy use can increase more than other climates. Regarding energy performance, the following building geometry factors have the highest to lowest influence: building orientation, plan shape, plan depth, and window-to-wall ratio.

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Keywords:

Energy-efficiency, geometric factors, early-stage design, high-rise office building, plan shape, orientation, window-to-wall ratio, compactness, energy modelling.

§ 3.1 Introduction

In the early phases of the design process, the design of a building may be influenced by several factors such as site limitations, client demands (e.g. maximum space efficiency for return of investment), functional and aesthetic quality, costs, building codes, urban regulations, and last but not least the desire of the designer/client to reduce the environmental impact resulting from energy consumption and CO_2 emissions.

During the early design phases, the decisions made by the designer can have a significant influence on the building's energy performance (Bragança et al., 2014). The general building layout is of great importance for minimizing the energy loads and for enabling passive design strategies. There is a growing awareness to use building performance simulation tools during the design process (Attia & De Herde, 2011). According to a survey conducted by Athienitis and Attia (2010), about 60% of energy models are created for the early stage design. Building shape and orientation together with the general design of the envelope are the main areas of focus for energy modelling during the early design phase.

§ 3.2 Overview of previous studies

The impact of building shape on energy performance has been investigated widely since the development of building performance simulation tools. Several studies have shown that a correlation exists between a building's compactness and its energy consumption (AlAnzi et al., 2009; Choi et al., 2012; Depecker et al., 2001; Ourghi et al., 2007; Pessenlehner & Mahdavi, 2003). Compactness of a building is defined as the ratio of the area of the external envelope (A) to the volume (V). Findings showed that compact shapes can result in lower energy consumption, especially in hot and cold climates (Susorova et al., 2013).

A number of studies researched the application of the relative compactness (RC) coefficient for creating predictive equations (Depecker et al., 2001; Ourghi et al., 2007; Pessenlehner & Mahdavi, 2003). Relative compactness shows the deviation of the compactness of a building from the most compact shape. An example is the study done by Pessenlehner and Mahdavi (2003). They examined the reliability of the relative compactness indicator for the evaluation and prediction of annual heating loads and the total number of overheating hours by running several thermal simulations on hypothetical buildings with residential use in Vienna. A total number of 720 combinations were generated from 12 shapes, 4 orientations, 3 glazing ratios (10%, 25% and 40%) and 5 alternatives for the distribution of glazing across the external walls. 18 modular cells (3.5×3.5×3.5 m) were integrated in different ways to create various building forms at a given volume. Using the cube as a reference shape, the relative compactness of the different hypothetical buildings was in a range between 0.98 and 0.62. They found that the respective correlation between heating load and relative compactness (RC) is reasonably high ($R^2=0.88$). Furthermore, they explored the accuracy of the proposed regression equation to predict the heating load of five distinct shapes with the same RC value (0.86). The simulated results deviated from the predicted values in a range between -15% to +10%, which indicates the reliability of RC for assessing heating loads in buildings. However, the predictions showed a large deviation (-80% to +130%) in case of overheating predictions.

Depecker et al. (2001) investigated the relationship between shape (shape coefficient) and the energy consumption for heating of buildings in a cold, and a mild climate at the northern hemisphere. For the evaluation of the building's thermal behaviour a calculation method based on weighting factors was applied. In their study, sixteen cubic elements (5.4×5.4×5.4 m) were aggregated under two main categories of single- and multi-blocks to create fourteen building morphologies. For all buildings, the largest façade was facing along north-south and the proportional percentage of glazed area to external walls was the same in all cases (south: 58%, east and west: 17% and north: 8%). The correlation between the energy consumption for heating and the shape coefficient was investigated for the studied shapes. The results showed that a good linear correlation ($R^2=0.91$) existed in the cold climate and that the shape coefficient turned out to be a good indicator to assess the energy use for heating. In contrast, a weak correlation was found in case of the mild climate. Due to long periods of sunshine, the incident solar energy flux through glazing is high; hence, heat losses from the building skin have a smaller impact on the energy balance. As a result, the correlation between the shape coefficient and energy consumption was weak. Furthermore, the results showed that building shapes with higher total area of glazing (mostly non-monolithic forms) had less deviation from the regression line.

Ourghi et al. (2007) developed a calculation method that can predict the annual total energy use of different building forms using the energy results obtained from a reference shape with a square floor plan. For all building configurations, the total building volume of conditioned space remained constant. Using the DOE-2 simulation tool, they came up with a correlation equation that can predict accurately the relative annual total building energy use as a function of three parameters, including relative compactness, glazing area and the solar heat gain coefficient (SHGC) of the glazing. Furthermore, they found the impact of the insulation level of the building envelope to be insignificant. However, this equation is only applicable for cities with cooling-dominated climates and the result is only valid for buildings that have the same floor area and the volume of the reference building.

AlAnzi et al. (2009) conducted an investigation on several plan shapes with different geometric dimensions, window-to-wall ratios (WWRs) and orientations for the hot and arid climate of Kuwait. They found that the annual total building energy use for all building shapes decreases as the relative compactness increases. A change of the glazing area from 50% to 0% (no glazing) resulted in the same trend; an increase of RC leads to a reduction of energy use. Additionally, they found that orientation has an impact on building energy use, its effect however being almost independent of the building's shape, especially for lower values of the window-to-wall ratio. It should be noted that their approach for the selection of building shapes can be subject of debate since a large number of the analysed plan configurations were not appropriate for the architectural design of office buildings (e.g. 2 m plan depth or no glazing for all directions).

Few studies took real case buildings to identify the impact of building shapes on energy consumption. A comparative case-study was conducted by Choi et al. (2012) on tall residential complexes in Korea in order to find the relation between building shape and energy consumption. They compared two plan forms: a Y-shaped and an I-shaped floor plan. For the purpose of comparison, the total electricity and gas consumption of households and common areas were calculated as a fraction of the total floor area in each case. They found that a linear I-shaped floor plan performed better in terms of total electricity consumption but consumed 10% more gas than the Y-shaped building. Furthermore, they mentioned that the architectural arrangement of units can influence the energy consumption. The Y-shaped building has three units around a central core while the two units of the I-shape building have just one shared wall and therefore a larger ratio of external wall surface area to their volume. In this study the insulation performance and the geographical location of both buildings were selected in a way to be almost identical. However, the influence of other design parameters such as WWR or building orientation was not discussed adequately where it may impact energy consumption.

Multiple studies have explored the optimal building shape by using numerical calculations (Kämpf & Robinson, 2010) or evolutionary algorithms such as the genetic algorithm (GA) (Kämpf & Robinson, 2010; Magnier & Haghighat, 2010; W. Wang et al., 2005; Yi & Malkawi, 2012). There are some arguments for and against the application of multi-objective optimization methods in comparison with conventional trial-and-error methods. New methods of optimization by using GA allow the user to explore site-specific complex building geometries without being restricted to a simple form (Yi & Malkawi, 2009). On the contrary, the simulations require a long time to run, the utilised method is complex and requires specialised expertise and is therefore not easy to be used by designers (Malkawi, 2004). Due to these constraints, designers are still relying on conventional trial-and-error methods for decision making at early-stage design despite the improvements that have been made in integrating optimization methods into simulation tools.

From the overview of previous studies, it can be highlighted that compactness is not the only building layout measure influencing energy consumption, although it might be the most influential parameter in climates that have a high demand for heating or cooling. Compactness does not reflect the three-dimensional massing of a building’s shape (e.g. self-shading), the transparency of the building enclosure (e.g. amount and distribution of windows), and the orientation of a building; hence, corresponding gains and losses are not being accounted for, even if they might have impact on energy consumption. In addition, most studies are on low-rises or a combination of building heights (dependent on the shape to be compared). As a result, this study aims to investigate the impact of building geometry of high-rise office buildings (40-storey) on the total energy use (and different energy end-uses), by investigating different combinations of plan shapes, plan aspect ratios, windows (percentage and distribution) and building orientations.

§ 3.3 Methodology

The overall methodological scheme of this research is summarised in Figure 3.1. The main objective of this study is to investigate the impact of geometry factors on energy-efficiency of high-rise office buildings in three climates. The geometry factors that have been investigated in this research are plan shape, plan depth, building orientation, window-to-wall ratio and window orientation. While comparing the climate and population density maps, it shows that the most densely populated cities around the world are mainly located in temperate, sub-tropical and tropical climates. These are the places where the majority of tall buildings are being constructed. As a result, this study aimed to answer the following questions in the context of the three climates:

- What is the most energy-efficient building shape for high-rise office buildings?
- Which aspect ratio of the floor plan performs best when considering the total energy use for heating, cooling, lighting and fans?
- To what extent can floor plan orientation influence the energy performance?
- What is the optimal range of glazed area for the different facades of high-rise office buildings?

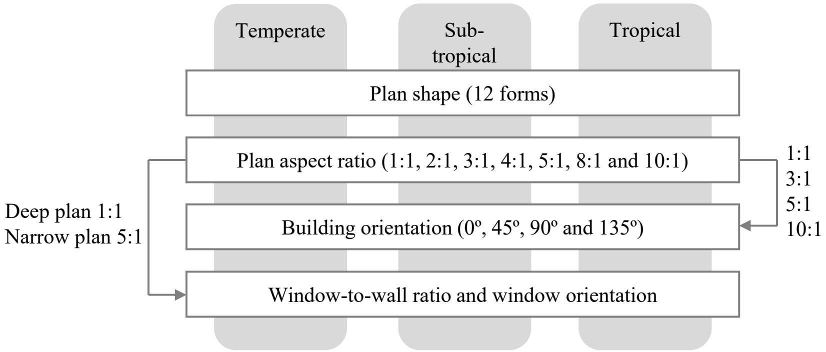


FIGURE 3.1 Methodological scheme of research.

§ 3.3.1 Building model

To investigate the effect of geometry factors, DesignBuilder version 4.7 was used. DesignBuilder is a powerful interface that incorporates the EnergyPlus simulation engine (version 8.3) to calculate building energy performance data. Building performance indicators that were used to express the simulation results are the annual total energy consumption and the breakdown of the total energy consumption into heating, cooling, electric lighting and fans. The energy figures presented in this paper are 'site energy' in kWh/m^2 of net floor area. Site energy is the amount of heat and/or electricity consumed by a building as shown on a utility bill. Since each floor level has one single thermal zone, the net floor area is equal to the area of the climatically conditioned space. The number of time steps per hour was set at 6 for the heat balance model calculation in this study. Increasing the number of time steps improves accuracy but increases the time it takes to run a simulation. A time step value of 6 is the suggested value by EnergyPlus for simulations with a HVAC system (and 4 for non-HVAC simulations).

The high-rise building models have a total floor area of 60,000 m^2 that is distributed over 40 storeys with identical floor plans. Different building shapes and floor plan aspect ratios are created by using an open plan office layout with a given floor area of 1500 m^2. Building models are simplified by defining one zone (activity) for the entire floor area. Each facade has a WWR of 50% that is to all façade elevations. The proposed building models have a variable-air-volume (VAV) dual-duct system to provide comfort. Since each storey has the same height and floor area, all models have an equal volume. However, the external surface area differs among the models; hence the extent of losses and gains through the envelope of the building. The inputs of the simulation for the properties of the building and the operation details are described in Table 3.1.

BUILDING PROPERTIES	
External wall insulation	U-Value: 0.35 W/m^2-K
Roof insulation	U-Value: 0.35 W/m^2-K
Glazing type A[1]	Dbl LoE (e2=.1) Clr 6mm/13mm Arg
U-Value	1.50 W/m^2-K
SHGC	0.57
Light transmission	0.74
Glazing type B[2]	Dbl LoE Spec Sel Clr 6mm/13mm Arg
U-Value	1.34 W/m^2-K
SHGC	0.42
Light transmission	0.68
Window-to-wall ratio	50%
Shading	Blinds (inside) with high-reflectivity slats
Shading control type	Glare
Maximum allowable glare index	22
BUILDING OPERATION DETAILS	
HVAC system type	Dual duct VAV
Heating	Gas-fired condensing boiler
Heating set point temperature*	20 °C
Cooling	DOE-2 centrifugal/5.50COP
Cooling set point temperature*	24 °C
Fan Power	2 W/l-s
Fan total efficiency	70%
Fresh air supply rate	10 l/s-person
Infiltration	0.5 ac/h
Lighting target illuminance	400 lux
Type of lighting	Fluorescent
General lighting power density	3.4 W/m^2-100 lux
Office equipment gain	11.77 W/m^2
Occupancy density	0.11 people/m^2
Occupancy schedule	Weekdays: 7:00 – 19:00; weekends: closed

*1- Glazing type A is selected for temperate climates. 2- Glazing type B is selected for sub-tropical and tropical climates. * The 20 °C and 24 °C set temperatures are indicating to air temperature and are active during occupancy hours.*

TABLE 3.1 Simulation inputs for building's properties and operation details.

TOC

§ 3.3.2 Sensitivity test

Before the actual detailed simulations took place, first a sensitivity analysis on certain parameters was done. For the purpose of simplification, almost all the building's properties and operation details were kept constant for all building models in the three climates, except for two envelope measures. For high-rises, the envelope has a higher impact on gains and losses due to higher exposure to solar radiation and wind; hence it is important to find the appropriate type of glazing and shading system that suits each climate type best (functionally, economically and energy wise). For temperate climates, the thermal transmission through a glass pane should be reduced by choosing a low U value glazing type. On the other hand, passive heat gains and daylight penetration are highly desired for reducing the heating and electric lighting loads (high SHGC and Light Transmission value). For hot climates, the glazing type should be able to limit solar heat gains into the interior (low SHGC), while not obstructing the transmission of light.

In order to have a better understanding of the relative variables, a sensitivity analysis (SA) was set up. SA is a way of testing a variable in order to find out its effect on the building performance. With regards to uncertain input parameters, different alternatives of glazing types and shading systems were simulated and the variation was observed. A rectangle shape was selected for the purpose of this sensitivity test. The reference building model has a plan aspect ratio of 3:1 and the long sides of the building are facing south and north. The results of the SA are presented in Table 3.2. This analysis showed that the demand for heating, cooling and lighting is highly responsive to changes in the glazing type and shading system.

In a temperate climate, using triple-glazed glass has relatively the same effect on the total building energy consumption as double-glazed glass. However, triple-glazed glass is more expensive and therefore might not be the ideal choice for climates with low to average heating requirements. As a result, a double-glazed low-emission clear glass was selected for temperate climates. Furthermore, it was found that spectrally-selective glazing is most favourable for climates that need high light levels and have a long cooling season like tropical and sub-tropical climates.

BUILDING PARAMETER	CLIMATE	VALUES	MAX. VARIATION kW h/m^2 - $(\%)^R$
Glazing type	Temperate	A $^{*,\text{max}}$, D $^{\text{min}}$	4.1 - (4%)
	Sub-tropical	A $^{\text{max}}$, B $^{*,\text{min}}$, D	12.6 - (17%)
	Tropical	A, B $^{*,\text{min}}$, C $^{\text{max}}$, D	21.8 - (16%)
Shading system	Temperate	E $^{\text{min}}$, F $^{\text{max}}$, G *	11.3 - (13%)
	Sub-tropical	E, F $^{\text{max}}$, G *, H $^{\text{min}}$	6.7 - (9%)
	Tropical	E, F $^{\text{max}}$, G *, H $^{\text{min}}$	18.1 - (15%)

GLAZING DESCRIPTION	U-VALUE	SHGC [1]	TSOL [2]	TVIS [3]
Type A. Dbl LoE (e2=.1) Clr 6mm/13mm Arg	1.50	0.57	0.47	0.74
Type B. Dbl LoE Spec Sel Clr 6mm/13mm Arg	1.34	0.42	0.34	0.68
Type C. Dbl Ref-A-H Clr 6mm/13mm Arg	2.26	0.22	0.13	0.18
Type D. Trp LoE (e2=e5=.1) Clr 3mm/13mm Arg	0.79	0.47	0.36	0.66

SHADING DESCRIPTION	CONTROL TYPE
Type E. Blinds outside	Solar: (120 W/m^2)
Type F. Blinds inside	Solar: (120 W/m^2)
Type G. Blinds inside	Glare: (glare index: 22)
Type H. Integrated shading system: overhang 0.5 m + blinds outside	Solar: (120 W/m^2)

** The selected glazing type or shading system.*
min= The design alternative that resulted in minimum energy use.
max= The design alternative that resulted in maximum energy use.
R= The maximum variation in relative terms.
1 SHGC= solar heat gain coefficient.
2 TSOL= direct solar transmission.
3 TVIS= light transmission.

TABLE 3.2 Sensitivity analysis of building envelope parameters.

External shading (e.g. outdoor blinds) performed better in terms of energy saving and solar control in all climates. A south façade (northern hemisphere) needs overhangs or fixed (stable) blinds, whereas east or west facades require more dynamic shading. However, the vulnerability of external shading to high wind speeds at high levels in tall buildings is an important barrier to their implementation. Indoor shading devices are not prone to damage due to wind. However, shading that covers the entire window surface reduces the view out and increases the need for artificial lighting and cooling (due to greenhouse effect). Hence, all simulations were carried out by using indoor blinds to control only glare.

TOC

§ 3.3.3 Location and climate type

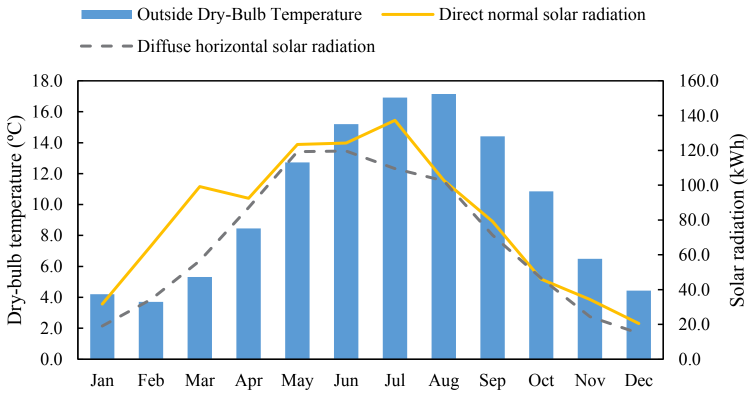
For each climate type a representative city was selected and the IWEC weather data (International Weather for Energy Calculation) of that city was obtained for energy simulations from the website of the US Department of Energy (US Department of Energy). The representative cities are Amsterdam for the temperate climate, Sydney for the sub-tropical climate, and Singapore for the tropical climate. A comparison of climatic features including heating degree days (HDD) and cooling degree days (CDD), along with mean monthly air temperature and solar radiation values can be seen in Table 3.3 and Figure 3.2 respectively. According to Table 3.3, the number of HDDs for Amsterdam is 2759, which is five times greater than for Sydney. The number of CDDs for Singapore is around 3657 which is considerably higher than for Sydney and Amsterdam.

CITY	CLIMATE TYPE	HDD	CDD
Amsterdam[1]	Temperate	2759	149
Sydney[2]	Sub-tropical	594	896
Singapore[3]	Tropical	0	3657

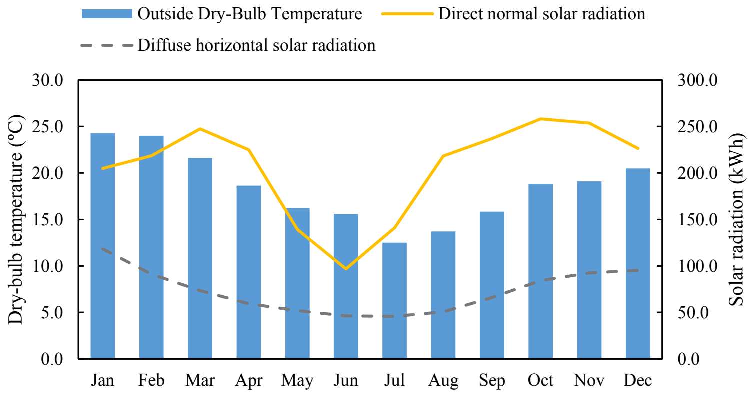
1-Amsterdam Schiphol Airport, Netherlands (4.77E, 52.30N).
2-Sydney Airport, Australia (151.17E, 33.95S).
3-Singapore Changi Airport, Singapore (103.98E, 1.37N).

TABLE 3.3 Celsius-based heating and cooling degree days for a base temperature of 18 °C for each city/climate (US Department of Energy).

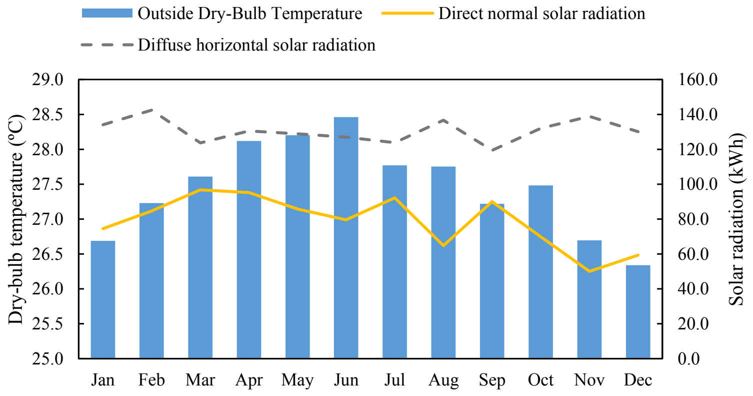
Amsterdam is located on the northern hemisphere in a temperate climate with cool summers and mild winters. The average monthly temperatures vary by 13.4 °C. The ratio of direct to diffuse radiation is equal in most part of the year. From the total number of daylight hours, 35% is sunny and 65% is cloudy or with haze and low sun intensity. The sun altitude peaks at 61.3° above the horizon at solar noon around the 21st of June, while at the winter solstice (around December 21st) it reaches its highest angle at 14.5°. Sydney is located on the southern hemisphere and has a humid sub-tropical climate. The mean monthly average temperatures have a low of 12.5 °C in July and a high of 24.3 °C in January. For Sydney, the ratio of direct to diffuse radiation is the highest among the three cities, and the majority of that radiation is direct. At lower latitudes close to the Equator, such as in Singapore, the solar radiation is intense, but to a great extent diffuse due to haze and clouds. The temperature is high throughout the year and remains relatively constant. At midday, the annual average value of the sun altitude is at 75° above the horizon, which is at a higher angle in comparison with Sydney (56°) and Amsterdam (38°).



1 Amsterdam



2 Sydney



3 Singapore

FIGURE 3.2 Mean monthly values of dry-bulb temperature and solar radiation adapted from IWEC weather data in: (a) Amsterdam, (b) Sydney, and (c) Singapore (US Department of Energy).

§ 3.4 Results and discussion

Space heating, cooling, ventilation and lighting account for the largest amount of energy consumption in buildings. However, the proportional energy use in commercial buildings differs from other building usages. In an office building, occupancy is during the day and lighting is paramount therefor. In recent years, the application of new types of equipment in commercial buildings has contributed significantly to the increase of electricity consumption. Besides, the type of air conditioning system and its efficiency, a building's operation details, and its construction properties have a big impact on energy use patterns.

The results obtained from the simulations have shown that the energy use for cooling could exceed that for heating for high-rise office buildings located in temperate climates such as in Amsterdam (see Figure 3.3). The heat accumulation from internal gains are an important component of the heat balance of an air-tight office building. The internal heat gains resulting from the presence of occupants, office equipment and electric lighting reduces the demand for heating in winter while increasing the demand for cooling in summer. In this parametric study, a single activity (generic office area) was used for the entire floor space. Allocating 100% of usable area to perform office work contributed to the increased use of electricity by electric lighting and equipment and therefore resulted in a higher amount of internal heat gains than expected. Furthermore, the results showed that fans account for roughly 15-20 per cent of the total energy use in a 40-storey office building with a VAV dual-duct system.

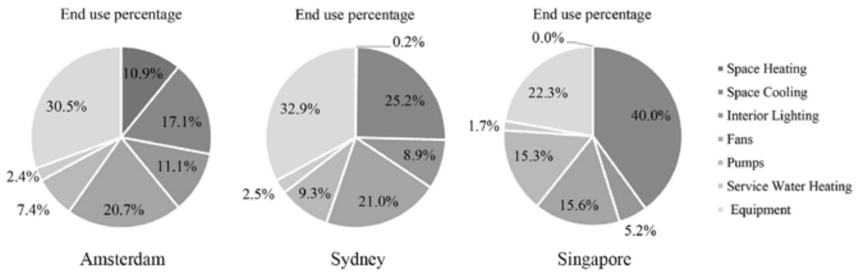


FIGURE 3.3 Breakdown of the total energy use in a simulated 40-storey office building with rectangular floor plan (3:1) in Amsterdam, Sydney, and Singapore.

In the following sections the effects of geometry factors on the building's energy performance will be discussed. Building performance indicators that were used to express the simulation results are the annual total energy consumption and the breakdown of total energy into different end-uses. In this study, the total energy consumption only includes heating, cooling, electric lighting and fans for these can be affected by the design of the building.

§ 3.4.1 Plan shape and building energy performance

Common shapes of floor plans for the design of high-rise office buildings were modelled in DesignBuilder and their energy performance was investigated to find the most energy-efficient form in the three climates. The study focused on twelve floor plan geometries including the circle, octagon, ellipse, square, triangle, rectangle, courtyard (or atrium), H shape, U shape, Z shape, + shape and Y shape, as can be seen in Table 3.4. In this table, some useful information regarding the compactness coefficient, window distribution and plan depth of the selected geometries are summarized. All building models have the same climatically conditioned floor area, but the ratio of surface area to volume differs from one shape to another. A building with a circular plan (shape 1) has the minimum ratio of surface area to volume; hence shape 1 is the most compact form. Since the volume of all plan shapes is equal, the relative compactness of the other eleven geometries can be calculated by dividing the external surface area of each building shape (A_{bui}) by the external surface area of the circle shape (A_{cir}).

In order to investigate the effect of plan shape on electric lighting loads, a plan depth indicator was defined. Current practice suggests for ideal daylighting access in office buildings to limit the plan depth to no more than 6-8 meter from a window (Wood & Salib, 2013). In this study the minimum range (6 m) was taken to calculate the plan depth indicator. This indicator shows the percentage of office spaces that can be accommodated within 6 m from the external façade. The quantity of electric lighting reduces when the percentage of peripheral offices along the external façade becomes higher.

Furthermore, the share of each façade from the total glazing area was calculated by using the following equation:

(Opening area on each façade / Total opening area) × 100

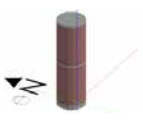
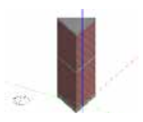
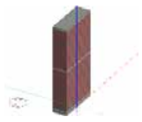
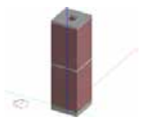
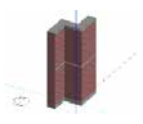
PLAN SHAPE	Shape 1	Shape 2	Shape 3	Shape 4	Shape 5	Shape 6
						
Share of each façade from the total glazing area (%)						
Floor plate dimensions	43.7 meters diameter	42.6 meters between facades	major axis: 60 minor axis: 32	38.7 meters between facades	51.1 meters altitude	67.1×22.4 length×width
Relative compactness	100%	103%	107%	113%	128%	130%
Plan depth indicator	47%	48%	52%	52%	58%	62%
PLAN SHAPE	Shape 7	Shape 8	Shape 9	Shape 10	Shape 11	Shape 12
						
Share of each façade from the total glazing area (%)						
Floor plate dimensions	14.0 meters from void	46.6×42.0 overall length×width 14.0 meters between facades	60.6×60.6 overall length×width 14.0 meters between facades	54.4×40.4 overall length×width 14.0 meters between facades	76.1×45.1 overall length×width 14.0 meters between facades	33.7 meters wing length 14.0 meters between facades
Relative compactness	157%	175%	175%	176%	176%	178%
Plan depth indicator	86%	87%	87%	87%	87%	87%

TABLE 3.4 Plan shapes isometric views, window distribution, relative compactness and plan depth indicator.

TOC

All the openings that are at an angle between 315-45° were assumed to have a north-facing orientation. Accordingly, the share of openings on the other three main directions was calculated as follows: 45-135° as east-facing windows, 135-225° as south-facing windows, and 225-315° as west-facing windows. In the case of shape 5, no window is oriented at an angle between 315-45°; hence, share of the north façade from the total opening area is 0%. While, each of the other three facades would have a one-third share of the total glazed area.

§ 3.4.1.1 Temperate climate

It is important to know the position of the sun in order to understand how the sun affects heat gains or heat losses in buildings. For higher latitudes, the sun path across the sky makes more seasonal variations. In summer, the sun path begins from north-east in the morning to a peak that is just below directly overhead in the noon, and then sets to the north-west in the evening. In winter, the sun rises south-east, paths a low arc across the sky, and sets south-west. Extending the long axis of a building along east-west has three advantages: it allows more daylight to enter a space, it limits overheating by west-facing exposures during summer afternoons, and it maximizes south-facing exposure for capturing solar thermal energy on winter days. Moreover, the high summer sun during mid-day can be easily blocked by overhangs or blinds without blocking diffuse daylight and view.

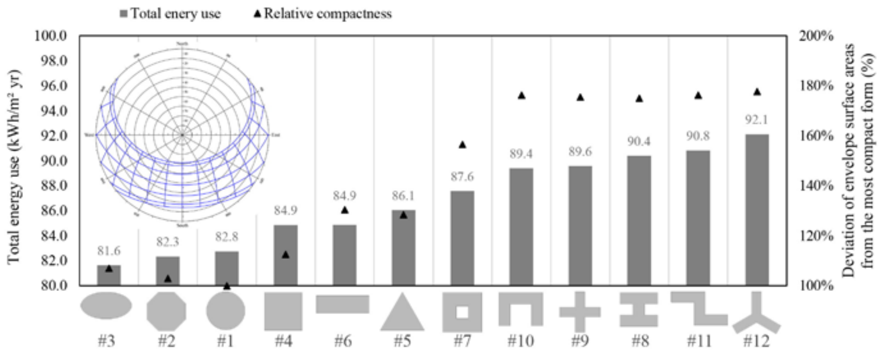


FIGURE 3.4 Building total energy use of twelve plan shapes (WWR= 50%) in association with their compactness in Amsterdam (4.77E, 52.30N).

PLAN SHAPE	Breakdown of annual total energy demand				Annual total energy demand	
	Heating/ conditioned area (kWh/m^2)	Cooling/ conditioned area (kWh/m^2)	Lighting/ conditioned area (kWh/m^2)	Fan/ conditioned area (kWh/m^2)	Total / conditioned area (kWh/m^2)	Percentile difference (%)
Shape 1	15.1	22.5	17.9	27.3	82.8	1.4%
Shape 2	15.2	22.6	17.1	27.4	82.3	0.9%
Shape 3 ®	14.9	22.5	17.2	27.0	81.6	---
Shape 4	15.2	23.5	17.5	28.7	84.9	4.0%
Shape 5	15.6	24.3	16.4	29.7	86.1	5.4%
Shape 6	15.5	24.2	15.8	29.4	84.9	4.0%
Shape 7	18.5	24.1	14.6	30.5	87.6	7.3%
Shape 8	19.2	24.4	15.6	31.2	90.4	10.7%
Shape 9	19.7	24.6	13.9	31.4	89.6	9.7%
Shape 10	19.5	24.3	14.6	31.0	89.4	9.5%
Shape 11	18.5	25.8	14.0	32.6	90.8	11.2%
Shape 12	18.9	26.0	14.4	32.9	92.1	12.8%

(WWR= 50%) in Amsterdam (4.77E, 52.30N).

TABLE 3.5 Breakdown of annual energy consumption per conditioned area for twelve plan shapes

The percentile difference in Table 3.5 indicates to a deviation in the total energy use between the most and least efficient forms. A large percentile difference by about 12.8% between the most and least efficient forms (shape 3 and 12 respectively) points to a dominant effect of plan shape on energy consumption in temperate climates. As shown in Figure 3.4, to some extent there is a correlation between the annual total energy use and the relative compactness in temperate climates. Generally, the larger the envelope surface area, the higher the amount of heat gains and losses through the building skin. As a result, compact shapes are more desirable for energy saving. On the other hand, the percentage of office areas that can be accommodated along the building perimeter increases when having a narrow plan building, so that less electric lighting is needed. Depending on the climate conditions, savings achieved by electrical loads and cooling loads (reduced internal gains due to less lighting) may compensate or outperform the increased fabric losses due to an elongated form (compare shape 1 with shape 3). However, for buildings with LED lighting (instead of fluorescent or incandescent) the effect of reduced internal gains due to less lighting become negligible.

The circle (shape 1) is the most compact form among the others; however, it is not the most energy efficient form in temperate climates. The results showed that a high-rise building model with an oval form (shape 3) has the lowest total energy use (about 81.6 kWh/m^2). The external surface area of the ellipse is about 7% larger than that of the circle and this will increase the amount of heat loss through the building envelope in winter. However, the heating demand of the ellipse building is slightly lower than of the circle (0.2 kWh/m^2). This slightly better performance of the ellipse in terms of heating demand is due to a higher percentage of south-facing windows for an ellipse shape plan (35%) in comparison with a circle shape plan (25%). According to Straube and Burnett (2005), the south façade can receive twice the heat gain of east and west façades in winter at a latitude of 45°. Considering the electric lighting demand, the circle has the maximum plan depth and a large part of the floor area may need electric lighting during most of the day time. The energy consumption for electric lighting is 17.2 and 17.9 kWh/m^2 for the ellipse and the circle respectively.

According to the simulations, a high-rise building model with a square shape (1:1) and a rectangle shape (3:1) both resulted in the same total amount of energy consumption in the temperate climate. The rectangle shape used more energy for heating, cooling and fans than its deep plan equivalent (square shape) due to additional transmitted heat through the façade. On the other hand, the rectangle form has higher percentage of peripheral offices along the external façade and therefore a better access to daylighting. The energy savings by electric lighting compensate for the extra HVAC energy demand. So, these two forms might be used interchangeably by designers when there are design restrictions to choose one of them.

The triangle (shape 5) and Y shape (shape 12) forms both showed considerable increased cooling demand compared to the other forms. East- and west-facing windows are a major factor in overheating of buildings in temperate climate. These plan shapes, that maximize east- and west-facing exposures, should therefore be avoided.

Almost 90% of office spaces can be placed within 6 m from the building enclosure when having an enclosed courtyard form (shape 7). It has less external surface area compared to linear forms. As a result, it performs better than linear shapes but is less efficient than other forms with higher compactness. It is worth to mention that the central atrium's height-to-width ratio is very limited in this case (11:1), so that it could not contribute efficiently to the reduction of energy demand for electric lighting. This indicated that atrium geometry has a crucial importance for the penetration of daylight to adjacent rooms.

Floor plan shapes that resulted in minimum lighting demand are the + shape (shape 9) and Z shape (shape 11). Shape 9 received the lowest amount of solar gains among the linear shapes during winter due to self-shading by extended wings. For that reason, it has the highest amount of heating energy use (about 19.7 kWh/m^2). This plan geometry may perform better in tropical climates in which solar gain protection is critical for achieving energy-efficient buildings.

TOC

§ 3.4.1.2 Sub-tropical climate

On the southern hemisphere, the geometry of a building should be reversed compared to on the northern hemisphere. Among the 12 studied building shapes, a 180° rotation of plan would have no impact on the building's energy performance except for asymmetrical shapes. Therefore, the orientation of only three shapes, namely shapes 5, 10 and 12, are reversed (180° rotation) for optimal energy results. In summer, building surfaces that receive the most sun are the roof and the east- and west-facing walls. In winter, the sun paths a lower arc across the sky, and the north-facing wall receives the most solar radiation while the south wall of a building receives limited solar radiation in summer (and in winter), only in the morning and evening.

In Sydney, the solar radiation is intense and to a great extent direct. The number of cooling degree days are almost twice as much as the number of heating degree days. High internal gains from windows, occupants, lighting, computers and office appliances limit the building's demand for heating drastically. As a result, the efficiency of plan shapes is mostly determined by the energy demand for cooling, fans and electric lighting.

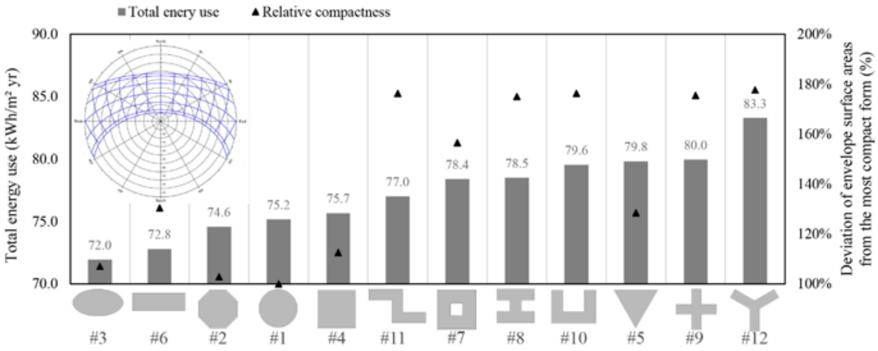


FIGURE 3.5 Building total energy use of twelve plan shapes (WWR= 50%) in association with their compactness in Sydney (151.17E, 33.95S).

PLAN SHAPE	Breakdown of annual total energy demand				Annual total energy demand	
	Heating/ conditioned area (kW h/m^2)	Cooling/ conditioned area (kW h/m^2)	Lighting/ conditioned area (kW h/m^2)	Fan/ conditioned area (kW h/m^2)	Total / conditioned area (kW h/m^2)	Percentile difference (%)
Shape 1	0.4	33.5	13.6	27.6	75.2	4.5%
Shape 2	0.4	33.6	12.8	27.7	74.6	3.7%
Shape 3 ®	0.3	32.3	12.7	26.5	72.0	---
Shape 4	0.4	34.2	12.6	28.4	75.7	5.1%
Shape 5	0.4	35.8	13.5	30.1	79.8	10.9%
Shape 6	0.3	32.8	11.7	28.0	72.8	1.2%
Shape 7	0.5	36.0	11.8	30.1	78.4	9.0%
Shape 8	0.5	36.3	11.3	30.5	78.5	9.1%
Shape 9	0.6	36.9	11.4	31.1	80.0	11.1%
Shape 10	0.5	37.1	10.7	31.3	79.6	10.5%
Shape 11	0.4	35.9	10.6	30.2	77.0	7.0%
Shape 12	0.4	39.1	10.3	33.5	83.3	15.7%

TABLE 3.6 Breakdown of annual energy consumption per conditioned area for twelve plan shapes (WWR= 50%) in Sydney (151.17E, 33.95S).

For the sub-tropical climate of Sydney, the results show that the ellipse (shape 3) has the lowest total energy use (72.0 kWh/m^2), while the highest energy use was found for the Y shape (shape 12) (83.3 kWh/m^2 or 15.7% higher than shape 3). According to the results, the amount of energy used for space cooling and fans is slightly lower in compact forms. The energy use for fans is calculated based on the supply air flow rate, pressure drop and fan efficiency. The supply fan only runs when either cooling or heating needs to be supplied to the zone. For elongated shapes, the increased length of ducts increases the energy use for fans due to higher pressure drops (compare shape 1 and shape 6). Contrary to this, a very deep plan like the circle shape would demand more electrical lighting; hence more cooling is needed to compensate the excessive internal gains by lighting and more energy is required for the distribution of cold air by fans.

The rectangle is the second most efficient shape after the ellipse. According to the results, the lowest cooling demand is around 32.3 kWh/m^2 and 32.8 kWh/m^2 for the ellipse and rectangle respectively. As can be seen, reducing the west-facing exposure is of great importance to limit overheating during the hot afternoon hours in summer. The compactness of the circle (shape 1) and the octagon (shape 2) are almost equal and therefore the energy use for cooling and fans are almost the same as well. Nonetheless, the 8-sided polygon resulted in 0.8 kWh/m^2 lower energy use for electric lighting, which is closer to that of the rectangle and the ellipse.

The Z shape (shape 11) has the best energy performance among the linear shapes and even outperformed the courtyard and the triangle (that both have higher relative compactness). The extended top-side wing of the Z shape design helps to minimize afternoon solar gains by providing self-shading for a part of the north- and west-facing walls. The H shape (shape 8) also benefits from self-shading by means of external wings, however the distribution of windows being not as effective for daylighting as the U shape (shape 10).

After the circle, the triangle has the second largest energy use for electric lighting. The two sides of the inverted triangle shape are facing toward morning and evening solar radiation during summer. Low sun angles in the morning and evening are a source of glare when daylighting is provided through east- and west-facing windows. For all building models, high reflective blinds are adjusted inside the building to provide visual comfort for office occupants. Shading is on if the total daylight glare index exceeds the maximum glare index specified in the daylighting input for an office zone. The high amount of electric lighting demand for the triangle shape is probably caused by longer shading hours, so that less daylight can enter the space.

§ 3.4.1.3 Tropical climate

At latitudes closer to the equator, such as Singapore, the solar radiation is intense and to a great extent diffuse due to clouds. The sun rises almost directly in the east, peaks out nearly overhead, and sets in the west. This path does not change much throughout the year and the average air temperature is almost constant. On the one hand, a major design objective is reducing the heat transfer through the external surfaces exposed to outside high temperatures. For this purpose, a compact shape has less surface-to-volume ratio and can save more energy. On the other hand, the shape and orientation of the building should minimize the solar heat gains to lighten the cooling load. East- and west-facing walls and windows are a major factor in overheating. Therefore, the best orientation of the building for sun protection is along the east-west axis. The design objectives above are often contradictory.

TOC

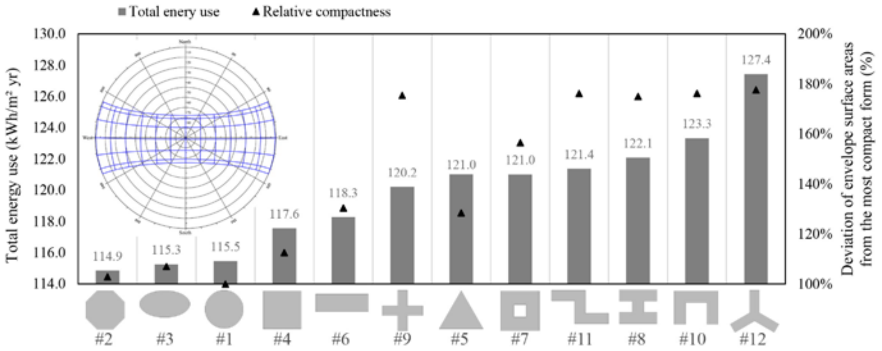


FIGURE 3.6 Building total energy use of twelve plan shapes (WWR= 50%) in association with their compactness in Singapore (103.98E, 1.37N).

PLAN SHAPE	Breakdown of annual total energy demand				Annual total energy demand	
	Heating/ conditioned area (kW h/m²)	Cooling/ conditioned area (kW h/m²)	Lighting/ conditioned area (kW h/m²)	Fan/ conditioned area (kW h/m²)	Total / conditioned area (kW h/m²)	Percentile difference (%)
Shape 1	0.0	75.4	11.7	28.4	115.5	0.5%
Shape 2 ®	0.0	75.5	10.8	28.6	114.9	---
Shape 3	0.0	75.5	11.3	28.4	115.3	0.4%
Shape 4	0.0	76.7	11.3	29.5	117.6	2.4%
Shape 5	0.0	79.0	10.4	31.6	121.0	5.4%
Shape 6	0.0	77.8	10.2	30.3	118.3	3.0%
Shape 7	0.0	79.0	10.6	31.4	121.0	5.4%
Shape 8	0.0	80.1	9.7	32.3	122.1	6.3%
Shape 9	0.0	79.6	8.7	31.9	120.2	4.7%
Shape 10	0.0	81.0	9.2	33.2	123.3	7.4%
Shape 11	0.0	80.5	8.7	32.2	121.4	5.7%
Shape 12	0.0	82.9	9.8	34.8	127.4	11.0%

TABLE 3.7 Breakdown of annual energy consumption per conditioned area for twelve plan shapes (WWR= 50%) in Singapore (103.98E, 1.37N).

In Singapore, cooling is paramount. Three shapes including the octagon, the ellipse and the circle require a lower amount of cooling energy and perform better than the others. The breakdown of annual energy consumption results for these three shapes indicates the superior function of the octagon shape for saving electric lighting which makes the octagon to have a better performance than the ellipse (+0.4%) and the circle (+0.5%).

TOC

The east and west-facing facades of the rectangle (shape 6) have the smallest portion of glazing area (glazing is only 12% on each side). Enclosing 1500 m^2 of floor area by a rectangle shape will increase the building's external surface area to 130% of the most compact form (shape 1). The results show an increase of total energy use by 3% compared to the most efficient form (shape 2).

The Y shape (shape 12) has the lowest energy performance. In tropical climates, cooling is the main end-use of energy; it considerably increases as the solar gains increase. In general, the risk of overheating is higher for buildings that have larger east- and west-facing walls. Having a wind turbine shape, about one third of the façade is irradiated half a day: during the morning the east façade is irradiated, and during the afternoon the west façade. As a result, shadings are required during a longer period to control the excessive glare, so that less daylight can enter the space. Moreover, the Y shape has the highest ratio of volume-to-external-surface area among all plan shapes (178%). Due to the aforementioned reasons, a high-rise building with a Y shape plan has the lowest performance of the investigated shapes, showing up to 11% increase in total energy use.

§ 3.4.1.4 Suitability of plan shape for architectural design

In this study, energy efficiency was the main indicator for investigating the optimal plan shape. Other factors that might play a role for selecting the plan shape are space efficiency, natural ventilation, material use, structure, and aesthetic qualities (Raji et al., 2016). Obviously, for two plan shapes that have almost the same energy performance, the priority would be with the one that can provide multiple benefits rather than mere energy efficiency. Therefore, it is worth to briefly discuss the suitability of plan shapes from different perspectives for architectural design of tall buildings.

In terms of space efficiency, the floor slab shape is of great importance. It influences the interior space planning and structural system. Generally, the planning and furnishing of right angled or asymmetrical shapes are easier than floor slabs with sharp corners, and curved or irregular shapes. Furthermore, the plan shape can affect the choice for the internal circulation pattern; hence the space efficiency. In case of H shape, + shape or Y shape more floor area is taken up by corridors due to longer circulation routes in comparison with compact forms with a central service core. This may reduce the percentage of usable space.

The application of natural ventilation has a major impact on selecting the plan shape. Narrow plan depth and aerodynamic building form (e.g. circle or ellipse) can assist in natural ventilation. The aerodynamic form encourages the flow of wind around the external envelope and into the building from a wide range of directions (Wood & Salib, 2013). This also reduces turbulence around the building and improves pedestrian comfort at street level. The narrow plan depth facilitates the flow of air across the space and enhances the effectiveness of natural ventilation. In contrast, for buildings with a deep plan cross-ventilation can hardly occur, so that buildings require vertical shafts such as an atrium or solar chimney to facilitate natural ventilation. The application of large elements like that can minimise the efficient use of floor space (Wood & Salib, 2013).

Looking from the structural perspective and material use, asymmetrical compact forms, with the structural and functional core in the centre, are more resistant to lateral loads (e.g. due to wind or earthquakes) and require less material for the bracing structure (Dobbelsteen et al., 2007). On the other hand, the surface of curvilinear shapes (circle or ellipse) represents a smaller physical barrier against wind as compared to flat surfaces (square or rectangle), so that wind loads significantly reduce. Shape (size and configuration of the floor plan) is the most important cost driver for the construction of tall buildings. It can contribute up to 50% of total net cost due to its profound impact on the cost of structure and façade (Watts, 2013). The two key ratios that represent the relationship between shape and cost are: wall-to-floor ratio and net-to-gross floor area ratio. The latter determining the efficient use of floor space. While the former represents the amount of wall area that is required to enclose a certain area of floor space. From a cost perspective, the lower wall-to-floor ratio is better, so that a compact shape is the most economical choice (Watts, 2013){Watts, 2013 #20}.

Elongated floor plates that have an increased perimeter area (or deep plan shapes that have a central atrium) are favouring shapes for daylight access and views out in workplaces (Wood & Salib, 2013). However, the elongated sides should not be oriented toward east or west; since there is a risk of overheating and glare discomfort. Curvilinear shapes can provide a panoramic view to outside and improve the aesthetic qualities of design. Curvilinear shapes might also contribute in building's energy efficiency and provide more sustainable solutions (Wilkinson, 2013).

§ 3.4.2 Plan depth and building energy performance

The optimal balance of plan depth and building external surface area for energy efficiency of a 40-storey office building was investigated by modelling seven aspect ratios of an equiangular four-sided shape with 1500 m^2 of office area per floor (Table

3.8). The aspect ratio is a measure of the building's footprint that describes the proportional relationship between its length and its width (x:y). For an equal floor area, changing the aspect ratio will result in different external surface area and plan depth. An aspect ratio of 1:1 represents a square plan shape which has the lowest envelope area and the largest plan depth (38.7 m) among the rectangular shapes. Other aspect ratios have been made by extending the length of the floor plans along the east-west axis. So, the long sides of the building will face in the direction of north and south.

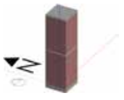
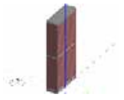
PLAN ASPECT RATIO	1:1	2:1	3:1	4:1	5:1	8:1	10:1
Building shape							
Share of each façade from the total glazing area (%)							
Floor plate dimensions length × width	38.7×38.7 meters	54.8×27.4 meters	67.1×22.4 meters	77.5×19.4 meters	86.6×17.3 meters	109.5×13.7 meters	122.5×12.2 meters
Relative compactness	100%	120%	130%	140%	150%	180%	197%
Plan depth indicator	52%	56%	62%	68%	74%	89%	98%

TABLE 3.8 Plan aspect ratios and the results of building energy performance in three climates.

The building performance simulation results of the seven plan aspect ratios are provided in Figure 3.7 and appendix A. In temperate climates, the most compact form (1:1) requires the lowest amount of heating and cooling energy. On the other hand, the deeper the plan, the harder it will be to naturally light the interior space, so that the electric lighting demand would be higher. Therefore, the 2:1 shape is slightly better than the 1:1 shape in the temperate climate. A large deviation in total energy use by about 12.8% can be observed between the most efficient (2:1) and least efficient (10:1) plan in the temperate climate. Having a plan aspect ratio of 1:1 or 3:1 can result in a minor 0.8% increase of the total energy use from the most efficient one.

In sub-tropical climates, the impact of plan depth on total energy use is less significant both in relative value (6%) and in absolute value (4.4 kWh/m^2). A plan aspect ratio between 2:1 and 5:1 is ideal in the sub-tropical climate of Sydney. Although reducing the external shell is critical for energy saving in tropical climates, reducing the plan depth can improve the access to daylight and compensate for the extra cooling energy demand due to solar gains. Consequently, the same as in the temperate climate, a plan ratio of 2:1 is the most efficient aspect ratio in the tropical climate, while a square plan shape (1:1) could be the next alternative for good energy-based design in tropical climates.

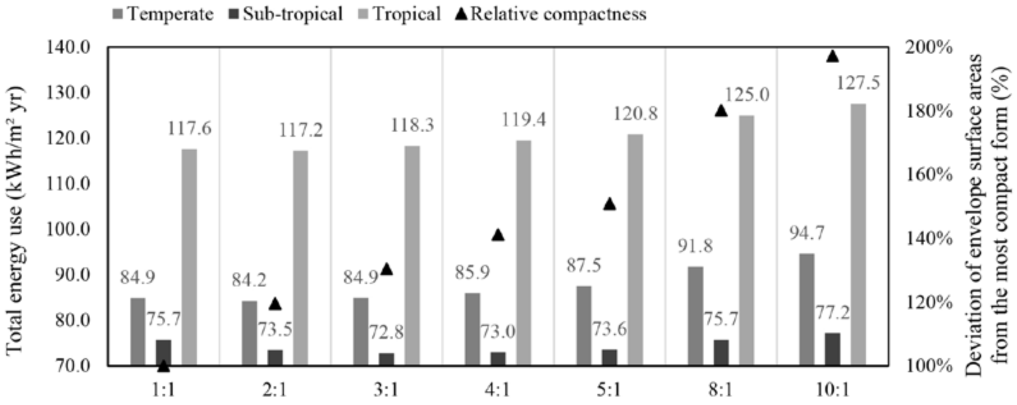


FIGURE 3.7 Building total energy use of seven plan aspect ratios (WWR= 50%) in association to their compactness.

§ 3.4.3 Plan orientation and building energy performance

In order to investigate the effect of plan orientation on energy consumption, four aspect ratios (1:1, 3:1, 5:1 and 10:1) from the previous section were modelled in four orientations; 0°, 45°, 90° and 135°. A zero-degree orientation means that the long sides of the building will face in the direction of north and south. Other orientations were made by rotating the buildings clockwise with respect to the north. As a result, a total number of 14 models were simulated and their energy performance analysed. A zero-degree orientation always resulted in the lowest energy consumption, while rotating the building 90° increased the energy use of the building to a large extent (Figure 3.8). In that orientation (0°) the building can make optimal use of solar gains on south facades in colder climates in winter and optimally keep out solar radiation in the early morning or afternoon in warm climates or in colder climates in summer.

The largest impact of orientation was observed for the sub-tropical climates (up to 32%) when the building is oriented at 90° and for the minimum plan depth (10:1). The effect of changing orientation is smaller for the temperate and tropical climates when the worst orientation is adopted compared to the optimal results; showing +15% and +8% increase respectively. Compact forms (deep plan buildings) are less sensitive to changes in orientation. In all climates, a building oriented 45° consumed less energy for electric lighting than one oriented 0° when the building has a deep plan (1:1). However, the increased overall energy demand caused by extra heating and cooling loads beat the energy saving in electric lighting. Our results are in good agreement with the findings in Florides et al. (2002). They found that the thermal loads of a square-shaped building reached its minimum value when facades are directly oriented toward the four cardinal directions. Our findings also determined that a 0° rotation from the north is the optimal orientation for gaining heat in cooler climates (temperate) and for controlling solar radiation in warmer climates (sub-tropical and tropical); this is in line with the findings of earlier studies (Abanda & Byers, 2016; Mingfang, 2002; Pacheco et al., 2012).

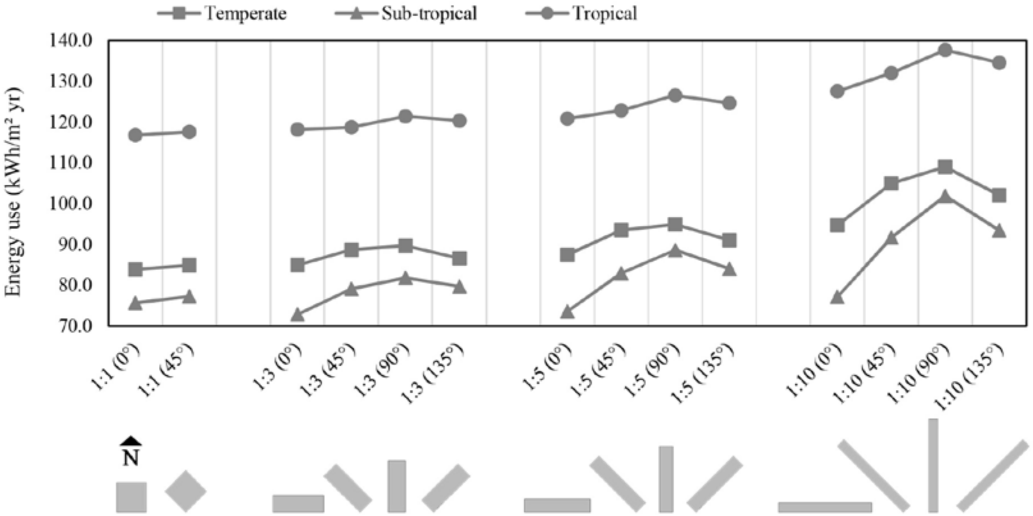


FIGURE 3.8 The energy impact of building orientation on four plan aspect ratios (WWR= 50%) in three climates.

§ 3.4.4 Window-to-wall ratio and building energy performance

Simulations were performed on a 40-storey office building to investigate the optimal size of the windows in temperate, sub-tropical and tropical climates. Since plan depth is a major determinant in finding the optimal solution, two plan scenarios were selected: a deep plan (1:1) and a narrow plan (5:1). Discrete window-to-wall ratio variations were studied, starting with a minimum value of 0% and increase with 10% increments to a maximum of 100%. For the deep plan scenario, the windows were distributed evenly among all directions. For the narrow plan scenario, the north- and south-facing walls (long sides of the building) are the focus of the investigation, while the east- and west-facing walls have no glazing.

Results for the optimal window-to-wall ratios are shown in appendix B. The energy efficiency indicator is the annual total energy use for heating, cooling, electric lighting and fans. Although there is an optimal WWR for each climate, the recommended values can be classified in four categories based on their degree of efficiency as shown in Figure 3.9. The most ideal WWR can be found in a relatively narrow range in which the total energy use deviates by less than 1% from the optimal results.

The energy consumption trend shows that in a temperate climate a window-to-wall ratio between 20% and 30% would result in the highest energy-efficiency for both the narrow and the deep plan due to lower heat transfer through the façade during winter and summer. Through using a similar approach - the integrated thermal and daylighting simulations in the temperate oceanic climates - earlier studies obtained the optimal WWR at slightly different ranges. Kheiri (2013) found the optimal value in the range of 20-32% for a building that was featured by a low-performance façade (U values for windows and walls were 2.4 W/m^{2}K and 2.6 W/m^{2}K respectively) and had no shading system. However, Goia et al. (2013) found the optimal value in the range of 35-45% through the integration of external solar shading devices with a high-performance façade (U values for windows and walls were 0.7 W/m^{2}K and 0.15 W/m^{2}K respectively). Therefore, it can be inferred that the optimal WWR value depends on the envelope properties employed in the simulations and can influence the results to some extent. The higher thermal resistance of the envelope, the lower impact of WWR on total energy use; hence, building can take advantage of larger windows for energy saving. Furthermore, our findings show that for WWR values smaller than 20%, the energy use for electric lighting incredibly increases. In a temperate climate, the upper limit of the recommended WWR is 60%; higher values result in up to 10% increase in total energy consumption due to additional transmission heat losses through the façade.

In a sub-tropical climate, the optimal WWR value is 35-45% for a deep plan and 30-40% for a narrow plan building. WWR variations that contain average performance (1-5% deviation) cover a relatively big range. For example, in case of the narrow plan scenario, window-to-wall ratios between 25-30% and 40-70% have average performance, but in a temperate climate this range limits to between 10-20% and 30-40%. Since the heating energy required is not significant for buildings in sub-tropical climates, a larger window area can result in a smaller demand for electric lighting; hence a better total energy performance. However, values higher than 80% and 90% are not recommended, respectively for a deep plan and narrow plan building because these have to high solar heat gains.

In a tropical climate, the optimal window-to-wall ratio is higher than that in a temperate climate but lower than in a sub-tropical climate. It is in a range of 30-40% for a deep plan and 25-35% for a narrow plan building. According to Figure 3.3, in the tropical climate, the share of electric lighting loads from the total end-use of energy is lower than in the sub-tropical climate. As a result, the energy savings for electric lighting (due to higher WWR values) in the tropical climate cannot be as much as in the sub-tropical climate. In addition, the difference between the indoor and outdoor air temperature in the tropical climate is not as high as in the temperate climate. So, in the tropical climate buildings can have a wider range of WWR values compared to that in temperate regions; especially when the proper type of glazing (low U value and solar heat gain coefficient) and the shading systems are employed in the facades for solar gain control.

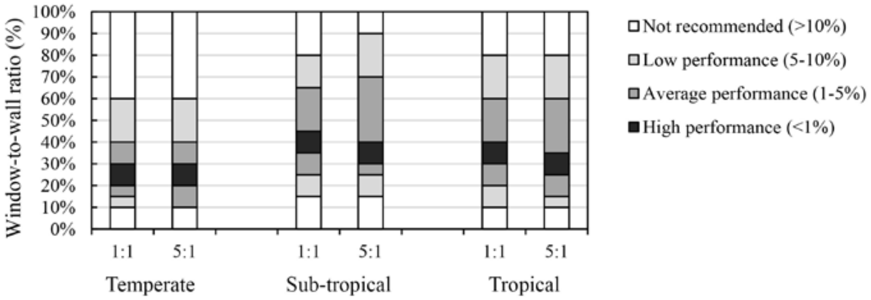


FIGURE 3.9 Recommended window-to-wall ratios for energy efficiency of a 40-storey office building with a deep plan (1:1) and a narrow plan (5:1) in temperate, sub-tropical, and tropical climates.

§ 3.4.5 Window orientation and building energy performance

In the previous sub-section, optimal WWR values of the façade, were determined for two plan scenarios regardless of the window orientation. In this part of the paper, the effect of window orientation on the total energy demand of the building will be investigated. Discrete window-to-wall ratio variations were tested, ranging from 10% to 90%, in incremental steps of 10%. One side of the plan was the subject of change on every iteration while the WWR for the other three sides was kept at the optimal value that was previously determined. The inputs of the simulation for the optimal WWR are 20% for the temperate climate, 40% for the sub-tropical climate, and 30% for the tropical climate.

The investigation was carried out on the four main orientations of the deep plan scenario and the two north- and south-facing facades of the narrow plan scenario. For the purpose of readiness, few graphs containing simulation results for the effect of window orientation on total energy use and energy end-uses (heating and cooling) are not shown in the text, but they can be found in appendixes C, D, and E. Sensitivity of different window orientations to a change in the WWR value was analysed in regards to total energy use variations and the results are provided in Table 3.9. Accordingly, the recommended values of WWR for different orientations and climates are summarized in Figure 3.10. The efficiency indicator for defining the recommended values is the total of all energy end-uses. As can be seen in Table 3.9, the acceptable window-to-wall ratio can range from 10% to 90% depending on the effectiveness of different window orientations for energy saving. For WWR increments of less than 10%, the average energy performance from two consecutive WWR values was obtained. Recommended values represent a range of WWR in which the deviation of total energy use is smaller than 1% from the optimal value in each orientation.

CLIMATE TYPE / PLAN ASPECT RATIO		Temperate		Sub-tropical		Tropical	
		1:1	5:1	1:1	5:1	1:1	5:1
Recommended WWR value (%)	North	10-90	10-70	10-15	15-40	10-50	10-35
	East	35-60	No glazing	10-20	No glazing	10-20	No glazing
	South	65-75	25-35	10-70	10-40	10-80	10-55
	West	10-15	No glazing	10-20	No glazing	10-20	No glazing

TABLE 3.9 Recommended WWR value for different orientations and climates in which the deviation of total energy use is smaller than 1% from the optimal value in each orientation.

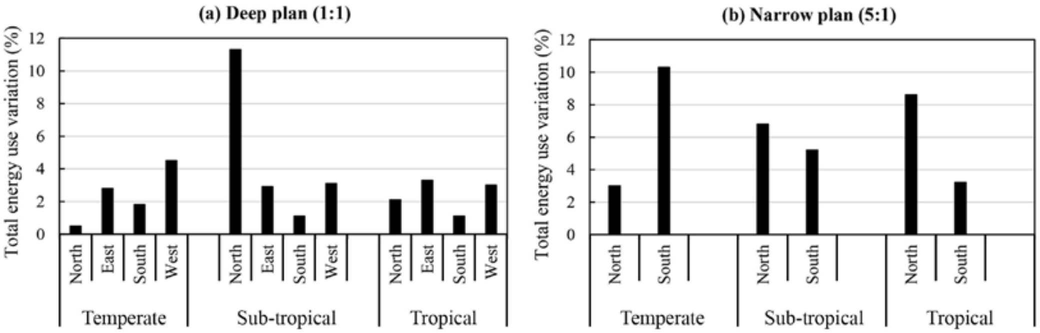


FIGURE 3.10 Sensitivity of different window orientations to a change in the WWR value (ranging from 10% to 90%) in terms of maximum variations in total energy use of a 40-storey office building with (a) deep plan and (b) narrow plan in temperate, sub-tropical, and tropical climates.

In temperate climates, the north-facing façade was found to be the least sensitive orientation, with no significant variation in energy use when relatively high insulation values were included in the simulations for windows (U value: 1.50 W/m^2K) and opaque surfaces (U value: 0.35 W/m^2K), and indoor blinds were adjusted only for glare control. In case of a deep plan, the ideal WWR for north-orientated windows can be found in a considerably wide range (10% - 90%) in which the deviation of total energy use is less than 1% from the optimal results. For the south-facing façade, the best energy performance is achieved with large windows when WWR is in a range of 65-75%. The optimal WWR for the west-facing façade is the lowest value of the investigated WWR range. According to Figure A3(a) and A4(a), the heating and cooling energy demand both increased significantly when the WWR percentage changed from 10% to 20%. The east-facing façade does not increase the cooling energy demand as much as the west-facing façade and does not contribute to capturing solar thermal energy on winter days as much as the south-facing exposure; therefore, the optimal range of WWR is 35-60%. In case of a narrow floor plan, lower values of the optimal WWR are achieved for the north- and south-facing facades due to a higher impact of the cooling energy use in the total energy balance. A wrong selection of WWR in the south-facing façade of a narrow floor plan can cause a greater increase of the cooling energy use (up to 68%) than of a deep plan building (13%).

In sub-tropical climates and for the deep plan scenario, the north-facing façade is the most sensitive orientation to a change in the WWR value, showing up to 11% deviation in total energy use. In order to achieve the highest energy performance (<1% deviation) it is important to reduce the size of east- and west-facing windows (10-20%) to protect the building against overheating, while for the south-facing exposure the total energy use is barley influenced by the WWR value. In case of a narrow plan building, the north- and south-facing facades present relatively similar trends and the recommended WWR ranges for those exposures are very close too (around 10-40%).

For all orientations in tropical climates, the cooling energy use is the driving force for selecting the recommended WWR range. The highest increases in cooling energy use are observed when a high WWR value is adopted for the west and east orientation, respectively. Therefore, the east- and west-facing walls should particularly avoid high WWR values. In the tropics and during mid-day, the building surface that receives the most sun is the roof since the sun paths a high arc across the sky. In case of a deep plan building, a wrong selection of WWR in north- and south-facing facades can cause a lower increase in the total energy use (+2.1% and +1.1%, respectively). For a building with a plan aspect ratio of 5:1, the recommended WWR values are found in a relatively narrow range; 10-35% for north-facing façade and 10-55% for south-facing façade.

§ 3.5 Research limitations and recommendations

There are several points that need to be further discussed for the proper use of findings and for the future development of this research. First of all, single-zone open-plan layout offices were defined for the entire floor space in all building models. Using one activity template has both advantages and disadvantages. On the positive side, it reduces the model's complexity, hence speeds up the simulation. In contrast, design potentials that some geometries might have in comparison to others, and their consequent effect on energy consumption cannot be reflected (e.g. usability of space). Furthermore, an increase of usable space can increase the internal gains due to occupancy, computers and lighting, which might have impact on the heating and cooling demands.

The optimal design solution depends on the exact set of variables for the properties of the building and the operation details. A sensitivity analysis was performed to obtain the glazing types and shading strategies for each of the climates used in this study. It was found that external shading performed better in terms of energy saving; however, the vulnerability of external shadings to high wind speeds at high levels in tall buildings is an important barrier for the application of them. Moreover, indoor shading devices are not prone to damage due to wind. They, however, reduce the view out and increase the need of artificial lighting and cooling. Hence, all simulations were carried out by using indoor blinds to control only glare. This means that cooling demands were probably less favourable than in reality.

Amsterdam, Sydney and Singapore were the representative cities for the investigation of the impact of geometric factors on energy use in the three main climate categories where the majority of tall buildings are being constructed. In general, for each latitude, the course of the sun and local microclimate conditions might influence a building's performance to some extent, so it is important to use the specific site location data as input for the simulations when the aim is finding the optimal results. The main objective of this study was to propose early-stage design considerations for the energy-efficiency of high-rise office buildings in three specific climates, so that these can be used to increase the awareness of designers regarding the consequences on energy consumption of decisions in the early phases of the design process.

Small to significant deviations may exist between the simulated and actual energy consumption for buildings. According to L. Wang et al. (2012) these deviations can be attributed to uncertainties related to the accuracy of the underlying models, input parameters, actual weather data and building operation details. There are some uncertainties related to the accuracy of simulation tool to consider thermal performance of curved shapes, and the optimal choice of number of timesteps per hour for heat balance model calculation. Furthermore, high-rise buildings are exposed to variable micro-climate conditions that changes gradually with the increase in building height. In tall buildings, the top levels are exposed to higher wind speeds and slightly lower air temperature as compared to the levels that are within the urban canopy. Additionally, at the higher altitude, the stack effect and wind pressures increase so that the air leakage through the building envelope and the consequent heat losses and gains might vary along the height. When using the weather data from a certain height, the impact of changing outdoor conditions and infiltration rates along the height could not be taken into account.

Finally, the investigation highlights that focusing on just one entry of the total energy balance is not correct and may lead to wrong conclusions. Therefore, determination of the optimal building geometry factor requires the analysis of heating, cooling, electric lighting and fans altogether, since these can be affected by the design of the building.

§ 3.6 Conclusion

The study presented in this paper investigated the effect of basic geometry factors on energy efficiency of high-rise office buildings in temperate, sub-tropical and tropical climates. Four geometric factors were the subject of investigation, which included plan shape, plan aspect ratio, building orientation and windows (percentage and distribution). A large number of energy simulations were performed using EnergyPlus as part of DesignBuilder. The results of the total annual energy consumption were used to define the optimal building geometry for each climate. This study shows the following:

- The effect of plan shape on building energy consumption is the highest in the sub-tropical climate (15.7%), and is lowest in the temperate climate (12.8%) and tropical climate (11.0%). The ellipse was found to be the ideal plan shape in all climates. It is the most efficient form in temperate and sub-tropical climates and the second efficient form in tropical climates after the octagon. Furthermore, the Y shape is the least efficient form in all climates.
- The effect of plan depth on total energy consumption is more dominant in the temperate climate (12.8%) than in the tropical (8.8%) and sub-tropical climate (6.0%). The optimal range of plan aspect ratio are 1:1 to 3:1 in Amsterdam, 3:1 to 4:1 in Sydney, and 1:1 to 3:1 in Singapore.
- In all climates, a rotation 0° from the north was found to be the ideal orientation for energy efficiency. In addition, a 90° rotation from the north is the least efficient orientation in all climates and for all plan aspect ratios (1:1 to 10:1) with an equiangular four-sided plan shape.
- Assuming that windows are equally distributed across building orientations, for a deep plan design, the optimal range of the window-to-wall ratio is 20-30% in the temperate climate, 35-45% in the sub-tropical climate, and 30-40% in the tropical climate. For a narrow plan design (with no glazing for the east- and west-facing walls), the optimal range is 5% lower, except for the temperate climate, which has the same values as for the deep plan design.
- The investigation also highlights the most sensitive orientations that potentially increase the total energy use (relative value) to a large extent for a wrong selection of WWR in different climates; those include the west-facing exposure in temperate climates (+4.5%), the north-facing exposure in sub-tropical climates (+11.3%), and the two facades facing east and west in tropical climates (up to 3.3%). Furthermore, the recommended WWR values are pointed out for different orientations and climates (see Table 3.9).
- The impact of geometric factors on energy-efficiency of high-rise office buildings in the three climates is summarised in Table 3.10. The recommended design options are classified according to their degree of energy performance under three categories: remarkable energy saving, average energy saving, and low energy saving. If the deviation of total energy use is greater than 10% from the optimal solution, the design alternative will be considered as not recommended. The results could be of assistance to make energy-wise decisions in the early phases of the design process.

	TEMPERATE					SUB-TROPICAL					TROPICAL				
Plan shape		A	B	C	D		A	B	C	D		A	B	C	D
<1%	Ellipse		+		+	Ellipse		+		+	Octagon	+			+
	Octagon	+			+						Ellipse		+		+
											Circle		+		+
1-5%	Circle		+		+	Rectangle	+				Square	+			+
	Square	+			+	Octagon	+			+	Rectangle	+			
	Rectangle	+				Circle		+		+	+ shape			+	
5-10%	Triangle					Square	+			+	Triangle				
	Atrium			+		Z shape			+		Courtyard			+	
	U shape			+		Courtyard			+		Z shape			+	
	+ shape			+		H shape			+		H shape			+	
											U shape			+	
>10%	H shape			+		U shape			+		Y shape			+	
	Z shape			+		Triangle									
	Y shape			+		+ shape			+						
						Y shape			+						
MD (%)	12.8					15.7					11.0				

Plan aspect ratio			
<1%	1:1, 2:1, 3:1	3:1, 4:1	1:1, 2:1, 3:1
1-5%	4:1, 5:1	1:1, 2:1, 5:1, 8:1	4:1, 5:1
5-10%	8:1	10:1	8:1, 10:1
>10%	10:1	---	---
MD (%)	12.4	6.0	8.8

Plan orientation	1:1	3:1	5:1	10:1	1:1	3:1	5:1	10:1	1:1	3:1	5:1	10:1
<1%	0°	0°	0°	0°	0°	0°	0°	0°	0° 45°	0° 45°	0°	0°
1-5%	45°	135° 45°	135°	---	45°	---	---	---	---	135° 45°	45° 135° 90°	45°
5-10%	---	90°	45° 90°	135°	---	45° 135°	---	---	---	---	---	135° 90°
>10%	---	---	---	45° 90°	---	90°	45° 135° 90°	45° 135° 90°	---	---	---	---
MD (%)	1.2	5.6	8.4	15.1	2.1	12.3	20.4	32.0	0.7	2.8	4.7	7.9

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TOC

	TEMPERATE				SUB-TROPICAL				TROPICAL			
WWR (%): deep plan (1:1)	**N**	**E**	**S**	**W**	**N**	**E**	**S**	**W**	**N**	**E**	**S**	**W**
<1%	10-90	35-60	65-75	10-15	10-15	10-20	10-70	10-20	10-50	10-20	10-80	10-20
1-5%	---	10-35 60-90	10-65 75-90	15-90	15-50	20-90	70-90	20-90	50-90	20-90	80-90	20-90
5-10%	---	---	---	---	50-80	---	---	---	---	---	---	---
>10%	---	---	---	---	80-90	---	---	---	---	---	---	---
MD (%)	0.5	2.8	1.8	4.5	11.3	2.9	1.1	3.1	2.9	3.3	1.1	3.0
WWR (%): narrow plan (5:1)	**N**	**E**	**S**	**W**	**N**	**E**	**S**	**W**	**N**	**E**	**S**	**W**
<1%	10-70	---	25-35	---	15-40	---	10-40	---	10-35	---	10-55	---
1-5%	70-90	---	10-25 35-55	---	10-15 40-75	---	40-90	---	35-70	---	55-90	---
5-10%	---	---	55-85	---	75-90	---	---	---	70-90	---	---	---
>10%	---	---	85-90	---	---	---	---	---	---	---	---	---
MD (%)	3.0	---	10.3	---	6.8	---	5.2	---	8.6	---	3.2	---

Energy efficiency of design options:
▓ *<1% (remarkable energy saving)*
▒ *1-5% (average energy saving)*
░ *5-10% (low energy saving)*
□ *>10% (not recommended)*

A: High space efficiency
B: Aerodynamic form
C: Narrow plan (NV & daylight access)
D: Less material use for external envelope

MD: Maximum deviation
N: North orientation
E: East orientation
S: South orientation
W: West orientation

TABLE 3.10 Early stage design considerations for energy efficiency of high-rise office buildings.

TOC

PLAN ASPECT RATIO	Breakdown of annual total energy demand				Annual total energy demand	
	Heating/ conditioned area (kW h/m²)	Cooling/ conditioned area (kW h/m²)	Lighting/ conditioned area (kW h/m²)	Fan/ conditioned area (kW h/m²)	Total / conditioned area (kW h/m²)	Percentile difference (%)
AMSTERDAM						
1:1	15.2	23.5	17.5	28.7	84.9	0.8%
2:1 ®	15.3	23.6	16.7	28.6	84.2	---
3:1	15.5	24.2	15.8	29.4	84.9	0.8%
4:1	15.6	24.9	15.0	30.4	85.9	2.1%
5:1	15.9	25.8	14.4	31.4	87.5	3.9%
8:1	16.7	27.8	13.0	34.3	91.8	9.0%
10:1	17.2	29.0	12.4	36.0	94.7	12.4%
SYDNEY						
1:1	0.4	34.2	12.6	28.4	75.7	4.0%
2:1	0.3	33.3	12.3	27.6	73.5	1.0%
3:1 ®	0.3	32.8	11.7	28.0	72.8	---
4:1	0.2	33.5	11.3	28.0	73.0	0.3%
5:1	0.2	34.0	10.9	28.5	73.6	1.1%
8:1	0.2	35.3	10.2	30.0	75.7	4.0%
10:1	0.2	36.1	10.0	30.9	77.2	6.0%
SINGAPORE						
1:1	0.0	76.5	11.3	29.5	117.6	0.3%
2:1 ®	0.0	76.7	10.8	29.7	117.2	---
3:1	0.0	77.8	10.2	30.3	118.3	0.9%
4:1	0.0	78.7	9.5	31.2	119.4	1.9%
5:1	0.0	79.7	9.0	32.1	120.8	3.0%
8:1	0.0	82.6	8.1	34.3	125.0	6.6%
10:1	0.0	84.2	7.7	35.7	127.5	8.8%

(WWR= 50%) in: (a) Amsterdam, (b) Sydney, and (c) Singapore.

TABLE 3.11 Breakdown of annual energy consumption per conditioned area for seven plan aspect ratios.

TOC

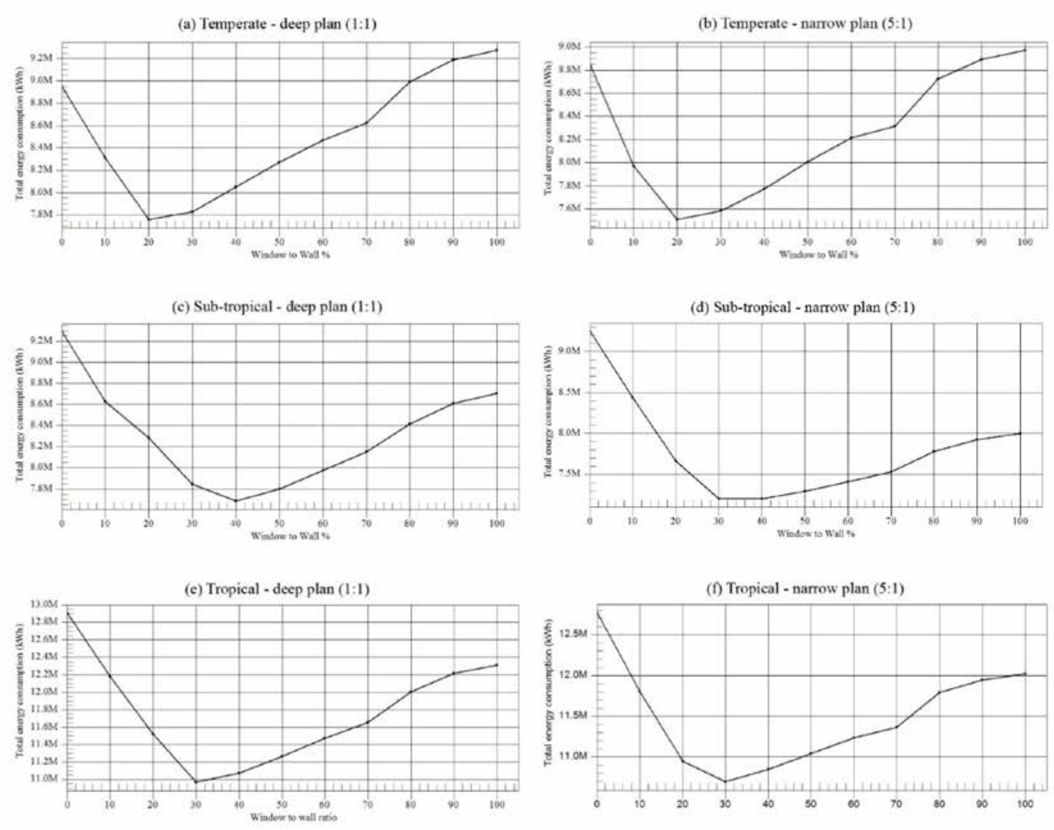

FIGURE 3.11 The optimal percentage of window-to-wall ratio for two plan types (1:1 and 5:1) in Temperate, Sub-tropical, and Tropical climates.

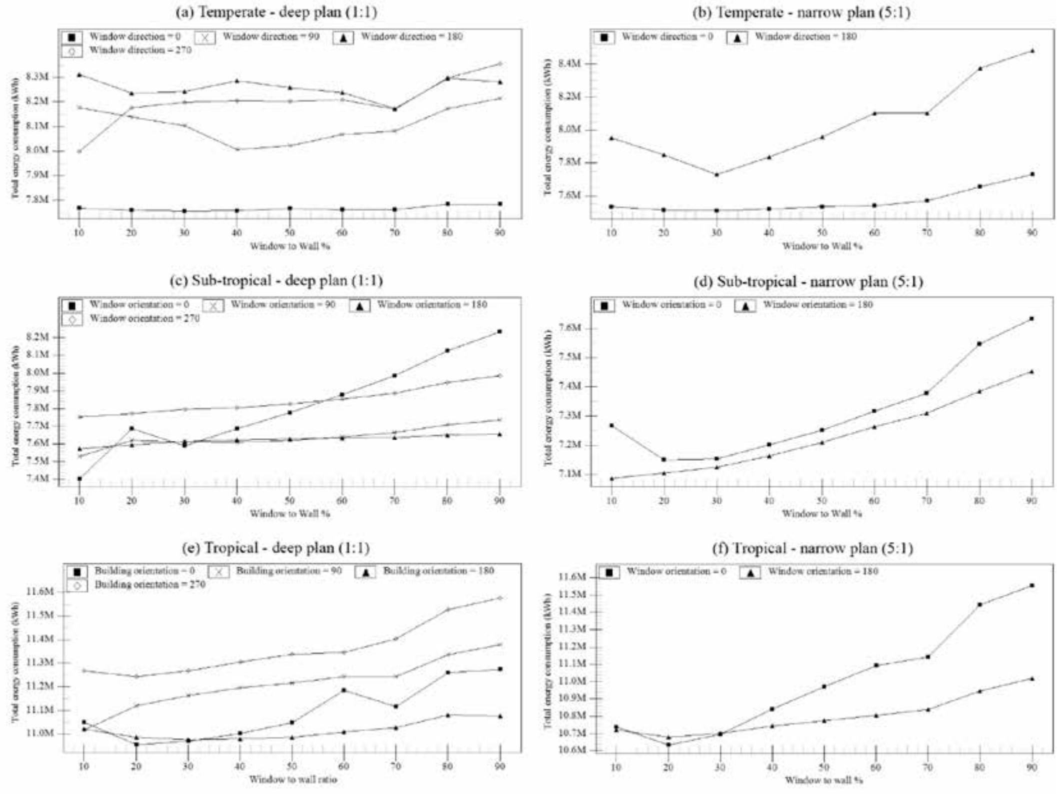

FIGURE 3.12 The optimal percentage of window-to-wall ratio in different orientations for two plan types (deep and narrow) in three climates.

Orientations: 0=North, 90=East, 180=South, and 270=West.

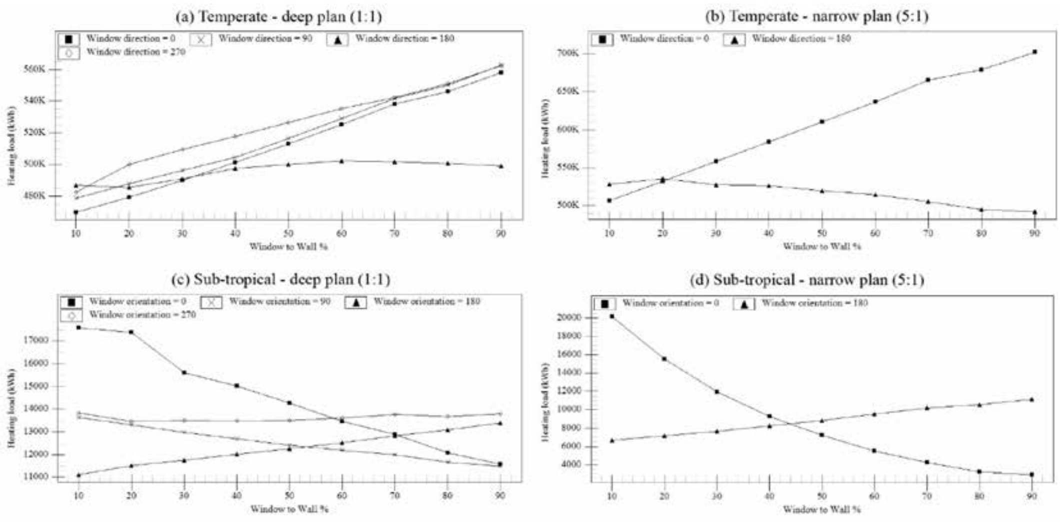

FIGURE 3.13 Relationship between energy use for heating and window-to-wall ratio in different orientations for two plan scenarios (deep and narrow) in temperate, sub-tropical, and tropical climates.

Appendix E

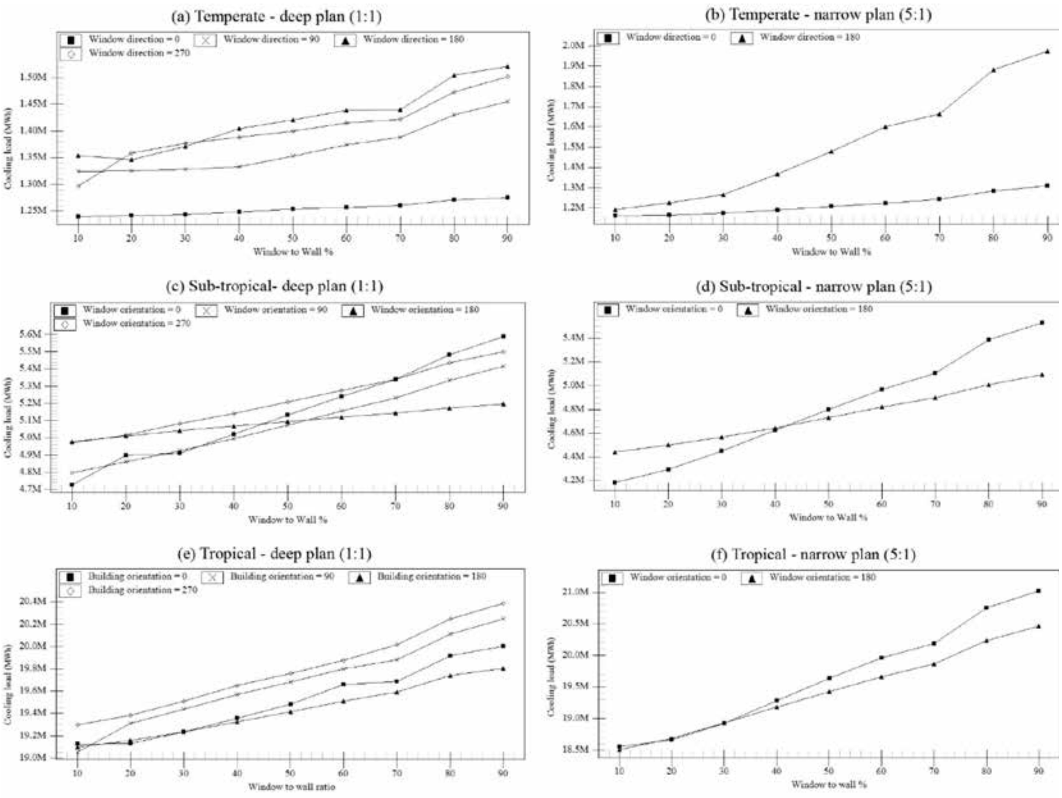

FIGURE 3.14 Relationship between energy use for cooling and window-to-wall ratio in different orientations for two plan scenarios (deep and narrow) in temperate, sub-tropical, and tropical climates.

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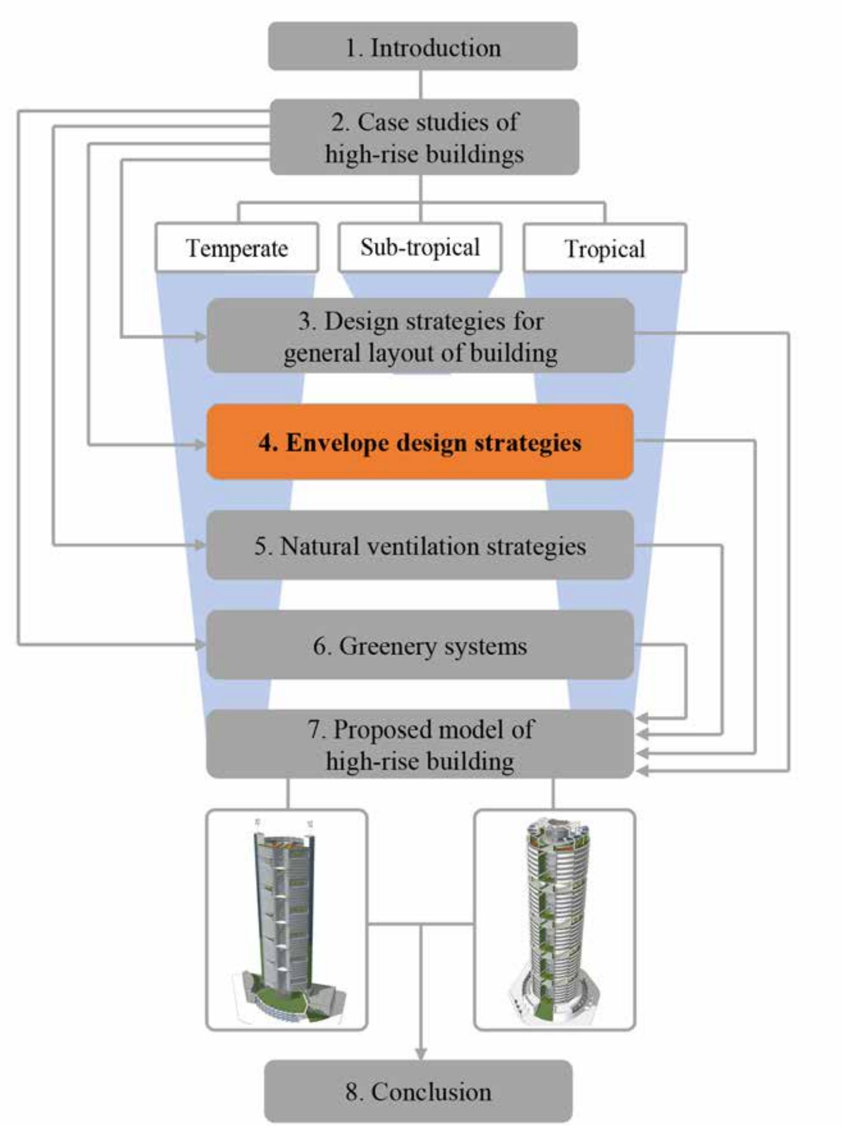
1. Introduction
2. Case studies of high-rise buildings
Temperate
Sub-tropical
Tropical
3. Design strategies for general layout of building
4. Envelope design strategies
5. Natural ventilation strategies
6. Greenery systems
7. Proposed model of high-rise building
8. Conclusion

4 Envelope design strategies

In the previous chapter the results indicated that the general building design is an important issue to consider for high-rise buildings. It was found that geometric factors could influence the energy use up to 32%. The second group of strategies is related to the envelope design. Chapter 4 aims to find energy-saving solutions for the envelope design of high-rise office buildings in temperate and tropical climates and to quantify their degree of influence. The 21-storey EWI building in Delft, the Netherlands, is selected as the representative for the temperate climate and the 65-storey KOMTAR tower in George Town, Malaysia, for the tropical climate.

In this regard, chapter 4 starts with an overview of previous studies on envelope design strategies. The rest of this chapter is divided in two parts: “part a” represents the temperate climate, and “part b” represents the tropical climate. For each part (climate), one section is dedicated to the methodology which describes the reference building, climatic data, simulated building model and validation of the model. In addition, a sensitivity analysis in line with a large number of energy performance simulations are performed to find out which building envelope parameters have a greater impact on the building’s energy consumption and should have first priority. Next, the effectiveness of different design alternatives for building envelope parameters is discussed in section 4.4 for the temperate climate and in section 4.7 for the tropical climate. Finally, the limitations of this research and general conclusions will be addressed at the end of this chapter.

§ 4.1 Introduction

During the last decade, international organizations have put considerable effort toward energy-efficiency in buildings as evidenced by EU Energy Efficiency Action Plans for 2020 and 2030 (European Commission, 2014; Pacheco Torgal et al., 2013). Currently, buildings account for almost 40% of total energy consumption and 36% of greenhouse gas emission in European countries (European Commission, 2007). The largest amount of energy consumption in commercial buildings is for space heating, cooling, ventilation and electric lighting. The building envelope is the interface between the indoor and the outdoor environment. It determines the amount of energy required to maintain thermal comfort. One of the best options for saving energy in retrofitting or new building projects is through designing the building envelope in an energy conscious way. Energy simulations, if well-validated, can help us to correctly apply design strategies to achieve considerable energy-savings (Heo et al., 2012; Yoon et al., 2003). These strategies can be beneficial for both the refurbishment of existing buildings and the decision making during the preliminary design stage of new buildings. The most effective strategies contributing in energy-saving of building design, however, are those applied before construction (Méndez Echenagucia et al., 2015).

The main objective of this study is to assess the role of building envelope design strategies on reducing the energy consumption of high-rise office buildings in temperate and tropical climates. Therefore, this study aims to answer to the following questions:

- Which envelope measures (or components) can influence the energy performance of high-rise office buildings in temperate climates more effectively?
- What are the energy-saving solutions for each design measure considering their effect on heating, cooling, lighting and overall energy consumption and which one perform better among others?
- To what extent would the combination of envelope strategies provide energy-saving?

For this purpose, an existing tall office building is selected as a typical high-rise building in the Netherlands and the energy usage pattern prior and after refurbishment is compared through a computer simulation. In this study, the energy efficiency indicator for the design strategies is the final energy use for heating, cooling and lighting. Verification of natural ventilation strategies requires a detailed investigation of air flow patterns. Therefore, a follow-up paper will investigate the effect of ventilation strategies via sky gardens, atria, cross ventilation and solar façades by means of CFD simulations, among others.

The envelope performance can be affected by three parameters: façade design parameters such as glazing type, window area and shading; building material properties such as thermal mass, insulation and airtightness; and site parameters such as building orientation and climatic features. The following section summarises the current literature regarding the optimisation of building design variables with the goal of energy-saving, with particular focus on envelope components.

§ 4.2 An overview of previous studies

High levels of energy-saving usually can be achieved by an optimal combination of several measures. Therefore, in this section we tried to cover studies which offer a multi-objective optimisation approach for the envelope design. These solutions aim to improve thermal comfort in buildings while reducing the energy consumption.

In a parametric study, Eskin and Türkmen (2008) investigated the effect of design variables such as insulation, thermal mass, external wall colour, shading, ventilation rate, window area and glazing type on the energy consumption of buildings in Turkey. A base case office building was developed for this parameter study and EnergyPlus was used to estimate the annual heating and cooling demand in four major cities with a different climate (Ankara, Istanbul, Izmir and Antalya). Finally, the relative impact of different design parameters on building energy use were presented for each city. Although Eskin and Türkmen presented a holistic overview of most of the envelope design parameters, occasionally the large number of selected design solutions prohibitively limited a deep investigation on some solutions such as shading.

Konstantinou and Knaack (2013) studied the energy effect of building envelope components and installation systems on refurbishment of middle-rise residential buildings constructed in the 1960s. Refurbishment solutions were assessed with Capsol for two Northern European cities located in the Netherlands and Germany. The energy efficiency indicator was the heating demand, as it is the dominant energy demand for those climates. The proposed design approach reduced the energy demand for heating by 90%. However, the economic feasibility of theses refurbishment strategies still needs to be investigated.

In search of the optimal balance between costs and energy benefits of refurbishment strategies, five types of dwellings in Belgium were selected by Verbeeck and Hens (2005). Energy-saving measures included in this study were: insulation, window (frame and glazing type), heating system and renewable energy systems. With regards to the optimal balance between costs and benefits of energy-saving measures, investing in thermal insulation should be the first priority, while investing in high-performance glazing and heating systems are second priorities. Renewable energy systems such as solar collectors and PV-panels were found to be the least profitable among the proposed solutions.

Capeluto and Ochoa (2014) used a simulation-based method to determine and rank energy-efficient retrofitting solutions in 13 urban centres from North to South Europe. Climate design strategies were defined through the use of psychrometric charts for each representative city and then translated into a conceptual façade module for evaluation through EnergyPlus. Finally, an energy ranking of each improvement and combinations of improvements was determined for a South-oriented façade for each climate. In Northern European cities, balanced ventilation with heat recovery, high-performance glazing and thick thermal insulation were the most influential solutions. For Central Europe, improved thermal insulation and glazing had the greatest impact on energy consumption reduction. In Southern Europe, where temperature and solar radiation intensity are higher, improved shading and glazing ranked higher.

Yıldız and Arsan (2011) used a sensitivity analysis (Monte Carlo method) in line with EnergyPlus to determine the most influential design variables for energy consumption reduction of apartment buildings in hot-humid climates. 35 building parameters were selected from nine major groups and applied on an existing apartment building in Izmir, Turkey. The result showed that for heating air infiltration had the highest impact while for cooling the aspect ratio of the building and cooling set-point temperature played a key role. Furthermore, window area and glazing properties were found to be influential variables on building total energy consumption.

Tavares and Martins (2007) used VisualDOE for the optimisation of design parameters of a public building in Portugal. Through a parametric study, the effect of the following design variables on annual heating and cooling energy were analysed: wall and roof type, window frame and glazing type, shading, HVAC system, infiltration rate, mechanical ventilation rate and temperature set-point. Taking the base case as a reference and optimising one variable at each step, they come up with an optimal solution that offers a considerable saving in energy by around 46% and 78% for cooling and heating respectively.

For the refurbishment of a residential high-rise building in Hong Kong, Cheung et al. (2005) investigated the effect of six passive strategies on cooling energy and peak cooling load. TRNSYS was used as the simulation tool, and the variables investigated were: thermal insulation, thermal mass, glazing type, window size, colour of external wall and shading. For a hot and humid climate, they found that the optimal combination of passive strategies can save up to 31.4% in annual required cooling energy and up to 36.8% in peak cooling load.

A literature study was conducted by Mirrahimi et al. (2016) to examine the effect of building envelope on energy consumption of high-rise residential buildings in tropical climates. They found that a strong relationship exist between various building components such as shading devices, external wall, external roof, external glazing and the reduction of energy consumption in buildings. Glazing type and external shading were defined as the two important contributors to the building energy usage and the peak cooling loads in tropical climates. This study reported that up to 25% saving in cooling energy load can be achieved with proper installation of external shading. The egg-crate devices were the most effective shading strategies in reducing indoor air temperature as they can block the solar radiation from a wide range of sun angles. However, this type of shading can result in less daylight access so that the increased use of electricity due to higher electric lighting demand needs to be taken into account. Furthermore, considerbale energy savings up to 19% for cooling loads was reported through the substitution of a single clear glass with the double-glazed low-e clear glass (see Mirrahimi et al. (2016) and references therein).

Ng et al. (2014) used a questionnaire survey to identify the feasibility of sustainable refurbishment methods for uplifting the energy performance of high-rise residential buildings in Hong Kong. For this purpose, 46 refurbishment measures were classified under 4 groups: building services, building envelope, building layout and renewable energy. They asked respondents (building owners and occupants) to indicate the degree of acceptability for each refurbishment measure. The result of the survey showed that improvements in the category of building services, such as lighting, appliances, mechanical ventilation and lifts, received higher attention from the owners and occupants. However, building envelope strategies, such as high-performance windows and shading were not easily accepted. Additionally, they mentioned the initial and operational costs, service life and degree of intervention as factors that affected respondents’ satisfaction to refurbishment strategies.

Among the passive design strategies for the building envelope, the double skin façade (DSF) technology has recently become a popular topic of study due to the complexity of thermal behaviour and air flow pattern involved in its design (Barbosa & Ip, 2014). Glazing properties (Chan et al., 2009), type and position of shading devices (Gratia & De Herde, 2007; Ji et al., 2007), structure and depth of cavity (Radhi et al., 2013; Rahmani et al., 2012) and size of air openings (Torres et al., 2007) are identified as parameters affecting the thermal and energy performance of buildings with DSFs. According to Barbosa and Ip (2014), finding the optimal combination of glazing type is a key element for the design of naturally ventilated buildings with DSFs. In order to achieve a higher air flow rate, it is essential to increase air temperature in the cavity. The application of single-glazing (instead of double-glazing) for the inner layer allows for higher solar transmittance; improving natural ventilation through the stack effect in the cavity. Vice a versa, double-glazing with higher thermal insulation is better to be placed at the inner layer to reduce heat transfer through the façade.

The location of blinds within the cavity has significant influence on air temperature and ventilation rate. The optimal position of blinds within the cavity was investigated by Gratia and De Herde (2007). They found that placing the blinds close to the inner layer

TOC

led to higher heat transfer from the cavity into the room; hence higher cooling demand. When blinds were placed in the middle of the cavity, they not only provided shading but also enhanced the air circulation on two sides. Considering the influence of shading control strategies on visual comfort and energy demand of office buildings in Seoul, Yun et al. (2014) suggested a blind slat angle of 0° is better in winter, in case when there is no need for glare protection. However, in summer a blind slat angle of 30° is the optimal configuration for energy-saving and glare control.

Radhi et al. (2013) performed a parametric analysis in order to assess the impact of different alternatives such as the cavity depth on reducing the cooling energy in a fully-glazed building with a DSF system located in hot arid climate of the UAE. They integrated building energy simulation with computational fluid dynamics analysis to establish and develop geothermal models. The results showed a reduction in heat transfer rate when the cavity depth reduced due to higher air velocity. However, surface temperature of the elements and solar heat gain increased with shorter cavity depth. Finally, they suggested a cavity depth between 70 and 120 cm can provide a balance between heat transmission and solar gain.

Ochoa et al. (2012), finally, used a combined design optimization method to find the optimum window sizes in the four main orientations by optimizing simultaneously for high visual comfort and low energy consumption. Building computer simulations performed on a hypothetical office room with a single external wall and a double-pane clear glass window (U-value = 1.7 W/m^{2}K) for the climate of Amsterdam. For normal office tasks, the standard illuminance target level of 500 lx was defined for electric lighting requirements. The results of this study determined the optimum window sizes for different orientations in a temperate climate as following: for North: 50-70% WWR, for South: 60% WWR, and finally for East and West: 50-60% WWR. However, it must be noted that shading elements are excluded from window design with the aim to make the optimization process less complex. Therefore, the optimum window-to-wall ratio might be different when adding shading elements or using a different glazing or façade type.

TOC

PART A / TEMPERATE CLIMATE

An assessment of energy-saving solutions for the envelope design of high-rise buildings in temperate climates; a case study in the Netherlands[3]

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Abstract

The building envelope is the interface between the interior of the building and the outdoor environment. A building's energy consumption to a large extent depends on certain envelope design elements. As a consequence, for achieving high levels of energy-saving in buildings, design measures with high impact should be firstly defined and then optimised. This paper aims at finding energy-saving solutions for the envelope design of high-rise office buildings in temperate climates. For this purpose, an existing tall office building is selected as a typical high-rise design in the Netherlands and the energy use prior and after refurbishment is compared through computer simulations with DesignBuilder. A sensitivity analysis in line with a large number of energy performance

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simulations showed which building envelope parameters have a significant impact on the building's energy consumption; hence need more consideration for improvement. The four measures selected for uplifting the energy performance of the building envelope include glazing type, window-to-wall ratio, sun shading and roof strategies. By taking the base case as a reference and optimising one parameter at each step, this study resulted in a high-performance envelope design that offers a considerable energy-saving by around 42% for total energy use, 64% for heating and 34% for electric lighting.

Keywords

Envelope design strategies, energy efficiency, high-rise office building, energy simulation, sensitivity analysis.

§ 4.3 Temperate climate: EWI building

The overall methodological scheme of this research is presented in Figure 4.1. This figure shows the different steps we took in the study. The subsections afterwards go into the steps more deeply.

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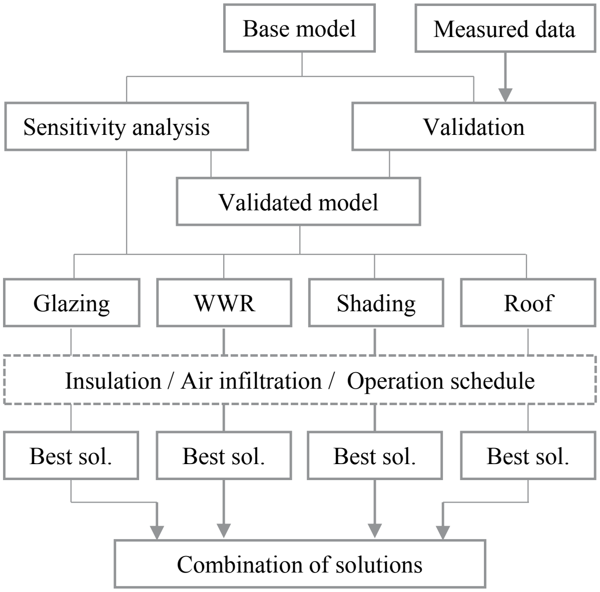

FIGURE 4.1 Methodological scheme of research.

§ 4.3.1 Reference building description

The case study concerns the building of the Faculty of Electrical Engineering, Mathematics and Computer Science (EWI) of Delft University of Technology. It is located in Delft, a city in the temperate maritime climate of the Netherlands. The Faculty of EWI has three main buildings, a high-rise office building with the lower two storeys reserved for educational facilities, a low-rise educational building and a high-voltage lab. Since this study aims to define energy-saving solutions for the envelope design of tall office buildings, only the high-rise building will be investigated. From the total floor area of this 21-storey building, only the first two levels have a different layout while all the upper floors have an identical floor plan with cellular offices. The building has a rectilinear narrow plan with cellular offices along the façade and a corridor in between. Its main façades have an East respectively West orientation, as shown in Figure 4.2.

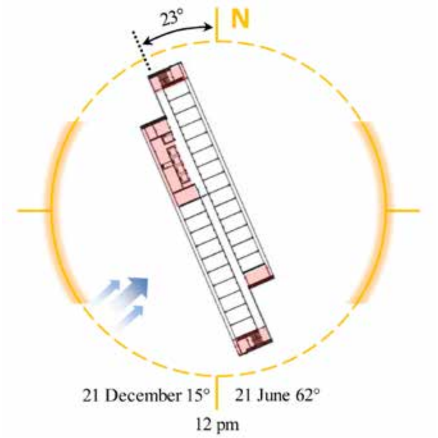

FIGURE 4.2 A typical office floor plan and the orientation of building.

The construction of the EWI building dates back to the 1960s when the development of double-skin façade technology was in its infancy and when building regulations had a limited energy scope. The energy consumption of this building, therefore, is relatively high (204 kWh/m^2) due to a high infiltration rate and high heat transmission through a low-performance façade. The building's envelope is built with a double skin façade (DSF). The DSF consists of single-pane tinted glass with a steel frame for the outer leaf and single-pane clear glass in a fixed window with wooden frame for the inner leaf and an air cavity between the two layers. The 95 cm cavity of the facade is horizontally continuous along the length of the facade, but vertically segmented at each floor. The cavity is accessible from two plant rooms at the ends of the corridor. Electric Venetian sun blinds are installed in this cavity in close distance to the external leaf; they can be controlled manually by the occupants.

In summer, the cavity in the façade is ventilated with outside air but for the majority of the year the air inlets are kept closed to minimise heat loss in cold weather. The fresh air is brought in from the centre of the façade and sucked out with the help of fans at the ends of the cavity's corridor. It means fresh air travels a long distance before being exhausted. The ventilation for the offices is separated from that of the cavity. The entire building is ventilated mechanically. Ducts in the façade cavity bring in fresh air for the office rooms. The stale air passes through openings in the dividing walls and is extracted in the corridor. The air flow diagram is presented in Figure 4.3.

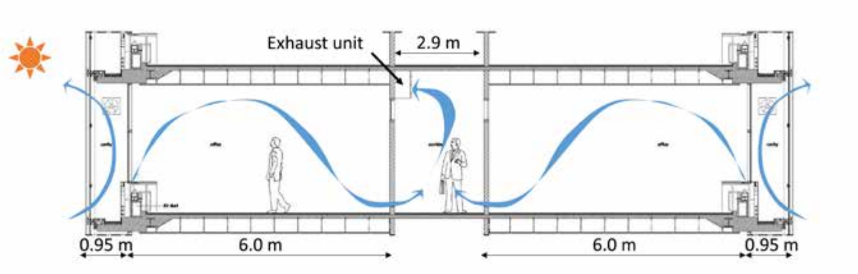

FIGURE 4.3 Air flow in the office area.

§ 4.3.2 Climate data

The EWI building is located in Delft, a city with a temperate maritime climate in North-West Europe (Latitude 51° 59´N and Longitude 4° 22´E). The climate is influenced by the North Sea and the Atlantic Ocean, with cool summers and mild winters. Two dominant climate features here are precipitation and wind. Rainfall is distributed relatively evenly throughout the year with a slightly dryer period from April to September. In fall and winter strong Atlantic low-pressure systems can bring strong winds which cause uncomfortable weather. Winds are omnidirectional but the predominant wind direction is South-West and the annual average wind speed is around 4.3 m/s.

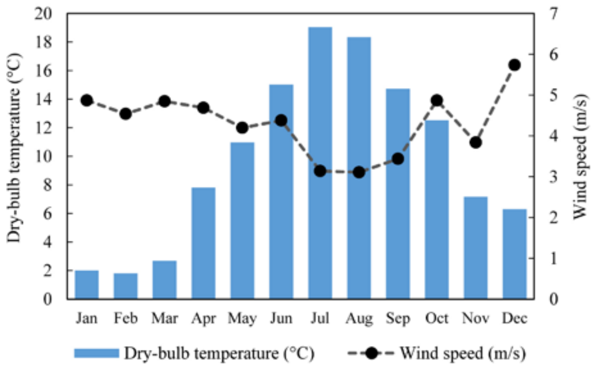

FIGURE 4.4 Mean monthly values of dry-bulb temperature and wind speed at Rotterdam Airport for the year 2013.

Detailed energy consumption figures of the EWI building were collected for the year 2013. Climate data of Delft was not available for the year 2013. For this reason, the performance of the building was simulated using 2013 weather data from the nearby KNMI weather station at Rotterdam-The Hague Airport (6.5 km South-East of the location).

§ 4.3.3 Simulated building model

The main objective of this study is to assess the role of building envelope design strategies on reducing the energy consumption of typical high-rise office buildings in temperate climates. For this purpose, the high-rise part of the EWI building is selected as a typical case building and the energy usage pattern prior and after the refurbishment is compared through a computer simulation. The DesignBuilder interface version 3.4 for EnergyPlus is used as a building energy performance simulation tool to create the model (see Figure 4.5). DesignBuilder is a validated tool that has been passed Building Energy Simulation Tests (BESTest) according to the EN ISO 13790 standard (2008) for the calculation of energy use for space heating and cooling and the ASHREA standard 140 (2011) for building thermal envelope and fabric loads.

FIGURE 4.5 3D model of the EWI building developed in DesignBuilder.

The real building properties and real climate data were used for making the simulation model. The properties of the construction materials used in this model are summarised in Table 4.1. The building model has multiple-zones and internal flows between spaces are taken into account. All of the zones (office rooms, corridor, etc.) are connected through small air grills (1.00 × 0.15) that are embedded at the bottom of the doors. The building model has a DSF with one external vent per 28 meter (three vents each side; two at corners 2.00 × 3.75, and one in middle 4.00 × 0.90) for natural ventilation inside the cavity, but there is no internal operable window and therefore the building fully relies on fans and air-conditioning for providing comfort conditions.

In order to cope with uncertainties related to model inputs, a sensitivity analysis (SA) was set up. SA consists of testing a variable (input) in order to see its effect on the building performance (output) (Calleja Rodríguez et al., 2013). Therefore, with regards to uncertain input parameters, different quantities of inputs were simulated and the variation was observed. The results of SA are presented in Table 4.2. A large number of computer simulations helped us to have a better understanding of the relevant variables and their degree of influence on the building's energy consumption.

Floor and ceiling	Vinyl sheet 3 cm, concrete 10 cm, air gap 30 cm, gypsum board 2 cm
Roof	Uninsulated flat roof: asphalt 1 cm, concrete 10 cm, air gap 30 cm, gypsum board 2 cm
Side walls	Reinforced concrete shear wall 100 cm (end sides of the building)
Partitions	10.5 cm brick plastered on both sides with white colour
Windows	DSF; outer layer: single-glazed tinted glass (10 mm); inner layer: single-glazed clear glass (10 mm)
Cavity	95 cm corridor type cavity (horizontally continuous but vertically segmented at every floor) and naturally ventilated in summer with the help of two exhaust fans
Window frame	Outer: aluminium; inner: wood
Shading	Manually operated Venetian blinds inside the cavity
HVAC system	Hot water radiator, mechanical ventilation (supply and extract)

TABLE 4.1 Construction details of existing building.

When performing SA, some variables could influence building energy consumption more than others. For optimization of building energy performance, variables with high-sensitivity should be targeted (Lam et al., 2008; Tian, 2013). The result of the SA gave us some clues about the building parameters which needs to be more investigated for energy-saving matter. For example, it showed that building loads is highly responsive to changes in the infiltration rate (44.2 kWh/m2) and glazing type (15.6 kWh/m2), so they should be in the first priority for the envelope refurbishment. Additionally, there are areas for the improvement of shading and the operation of external vents. For instance, using indoor blinds (base model) have relatively the same effect on the total building energy consumption as no shading device; hence, there is a need for a more in-depth energy analysis on different shading strategies in order to find the optimum solution. On the other hand, the effect of some parameters such as heating and cooling set point temperature, occupancy schedule and miscellaneous equipment found to be negligible.

BUILDING PARAMETER	UNIT	VALUES	MAX. OUTPUT VARIATION (KWH/M²)
Infiltration	ac/h	0.7, 1.5, 2*	44.22
External wall insulation	W/m^2K	0.25a, 0.37b, 2.22c*	1.87
Roof insulation	W/m^2K	0.15a, 0.37b, 1.91c*	3.16
Heating set point temperature	°C	20, 21*, 22	0.33
Cooling set point temperature	°C	23, 24*, 25	0.18
External vents operation schedule	---	summer cooling*, off	0.18
Occupancy density	$people/m^2$	0.11, 0.16*	2.74
Occupancy schedule	---	weekends (open*, close)	0.04
Minimum outside fresh air	l/s- person	4, 8*, 10	0.39
Mechanical ventilation per area	$l/s- m^2$	0.6, 1*, 1.6	0.45
Mechanical ventilation schedule	---	weekends (open*, close)	1.52
Miscellaneous equipment	W/m^2	0, 5*	0.14
Glazing type (outer pane)	---	clear, tinted*	15.6
Shading	---	no shading, indoor blinds*	1.16

** The base case settings of the reference model that led to the validated model; a best practice building; b recommended U-value by EURIMA (2007) for the Netherlands; c reference building (uninsulated).*

TABLE 4.2 Sensitivity analysis of building parameters.

§ 4.3.4 Calibration of the model

In order to test the accuracy of simulated model a calibration was set up. Figure 4.6 show a comparison of the measured and simulated energy use intensity (EUI) of the EWI building as far as it concerns total energy consumption and heating energy consumption. A simulation model is often defined as calibrated if it falls within a specific error margin. Maamari et al. (2006) suggested error margin of 10 - 20% as an acceptable range for percentile difference (PD) between the simulation results and the measured data. This comparison of the monthly energy use intensity showed that the absolute value of the percentile difference was equal to or less than 15% for the majority of the months except for the summer months. Figure 4.6 shows that in May, June and August the PD is more than 15% because the energy consumption for cooling is slightly underestimated by the simulation model during these months. At the EWI building, the air supply ducts are placed inside the cavity of the double-skin facade, as a result of which the chilled air is being heated along its way to the rooms. The efficiency of this cooling system is therefore low(er) and the electricity demand for cooling high(er) in the real building. The simulated model does not consider the extra cooling load due to the inefficiency of the distribution system, which explains the differences. Additionally, the energy use for heating accounts for more than 60% of the total energy consumption of the EWI building. As can be seen in Figure 6b, the simulated data are acceptably close to the measured data for heating energy consumption. As a result, the simulated model can be considered a sufficiently accurate base model for this study.

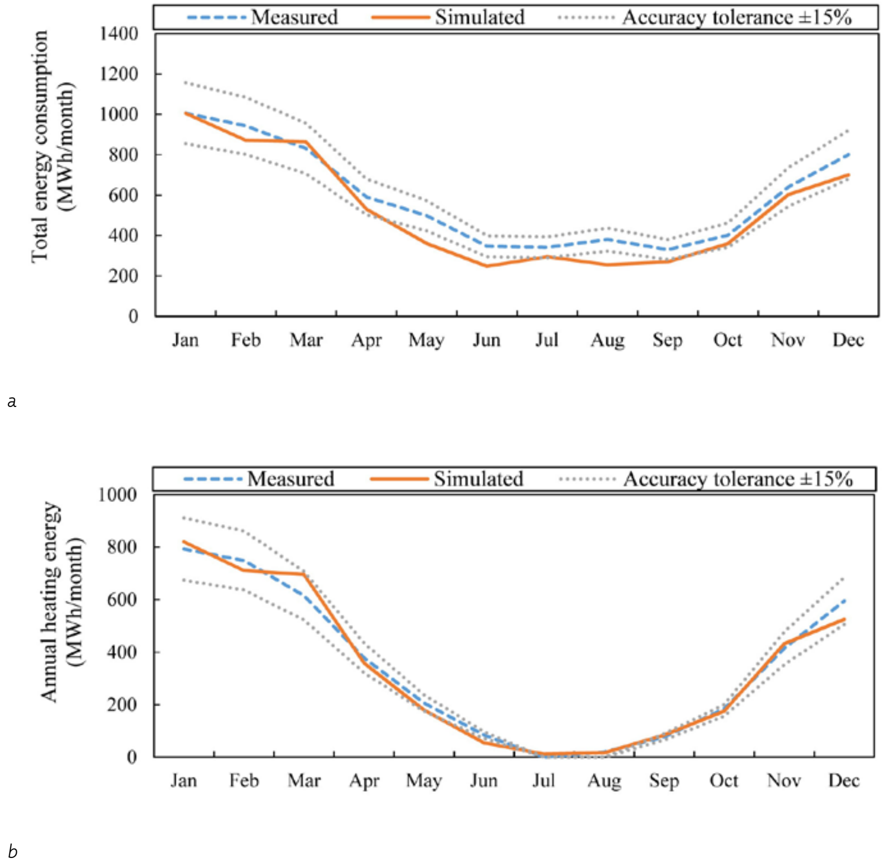

FIGURE 4.6 A comparison of simulated and measured data considering the total energy and heating energy consumption of the EWI building for the year 2013.

Using this model, a large number of computer simulations were run to evaluate the energy-saving potential of various design variables, as well as their combinations. As described in the following sections, retrofitting strategies for the building envelope grouped under 4 main categories were simulated using heating, cooling, lighting and total energy use as the efficiency indicator.

§ 4.4 Results and discussion

Through the simulations, the effect of each strategy is quantified as the percentage of reduction or increase in the total energy usage compared to the reference model. However, to have a better understanding of how retrofitting strategies can contribute in energy-saving during the heating and cooling seasons, the effect of each strategy will be discussed additionally on heating, cooling and lighting energy demand. In some cases, in order to apply a new strategy, there is a need to change the floor plan configuration, which means a different floor area of the conditioned space. In order to make different strategies comparable, the total energy consumption per conditioned area was used as an indicator.

§ 4.4.1 Glazing type

Façade performance depends to a large extent on the ability of glass panes to reflect, absorb or transmit solar radiation. When considering the influence of glazing type on daylight penetration, high-transmittance clear glass (high LT value) can lead to a reduction in energy consumption for lighting. This is also a preferable option for heating-dominant climates in which passive heat gains are highly desired (high g-value or SHGC). Solar heat gain coefficient (SHGC) is defined as a fraction of solar radiation that enters a building through the window. Thermal transmission through a glass pane is another influential factor for envelope performance which can be reduced by choosing a low U-value.

The tinted single-glazed DSF of the EWI building is replaced by different types of glass and façade systems to investigate their potential for energy retrofitting. In terms of heating, DSFs with a double-glazed clear pane (Type G & H) achieved more energy-savings compared to a triple-glazed window, irrespective of the position of single or double-glazed panes. However, choosing a double-glazed pane for the inner layer (Type G) resulted in the highest amount of energy-saving for space heating. For the summer case, the energy figures showed that the optimum window type is the reference design and that the highest cooling demand occurs when using a single-glazed clear glass. The reference design window benefits from a tinted glass pane which reduces the solar transmission considerably compared to a clear glass pane. In terms of cooling load, the difference is up to 58% in relative value but less significant in absolute value (15 kWh/m^2).

GLAZING TYPE	Annual heating demand			Annual cooling demand			Annual lighting demand		
	Total heating (kWh)	Heating / conditioned area (kWh/m^2)	Percentile difference (%)	Total cooling (kWh)	Cooling / conditioned area (kWh/m^2)	Percentile difference (%)	Total lighting (kWh)	Lighting / conditioned area (kWh/m^2)	Percentile difference (%)
Type A	4192952	216.7	4.0%	500114	25.8	-58.0%	428658	22.1	35.9%
Type B	4940923	255.4	-11.5%	384194	19.8	-45.4%	562911	29.1	15.9%
Type C	3995955	206.5	8.5%	447214	23.1	-53.1%	438709	22.7	34.4%
Type D	3994633	206.5	8.6%	302640	15.6	-30.7%	497627	25.7	25.6%
Type E®	4062323	225.9	----	195051	10.8	----	622062	34.6	----
Type F	3781715	210.3	6.9%	324183	18.0	-39.8%	565565	31.4	9.0%
Type G	3578574	199.0	11.9%	254995	14.2	-23.5%	569612	31.7	8.4%
Type H	3651551	203.0	10.1%	261262	14.5	-25.3%	572911	31.8	7.9%

Glazing description	Solar transmittance	U-Value (W/m^2-K)
Type A. [Sgl: Clr 10mm]	0.74	5.67
Type B. [Sgl: Tinted 10mm]	0.30	5.67
Type C. [Dbl: Clr 6mm/6mm air /6mm]	0.60	2.40
Type D. [Trp: Clr 6mm/6mm air/6mm/6mm air/6mm]	0.46	1.71
Type E. (Reference) DSF: inner pane: [Sgl: Clr 10mm]; outer pane: [Sgl: Tinted 10mm]	0.22	1.48
Type F. DSF: inner pane: [Sgl: Clr 10mm]; outer pane [Sgl: Clr 10mm]	0.55	1.48
Type G. DSF: inner pane: [Dbl: Clr 6mm/6mm air/6mm] - outer pane: [Sgl: Clr 10mm]	0.44	1.09
Type H. DSF: inner pane: [Sgl: Clr 10mm] - outer pane: [Dbl: Clr 6mm/6mm air/6mm]	0.44	1.09

TABLE 4.3 Simulation results obtained for different glazing type.

All of the solutions with clear glass have higher energy-savings for lighting compared to the original design. A deep air cavity (95 cm) in DSF forms a barrier against light transmittance, thus increasing the need for artificial lighting. Considerable reductions in energy use for electric lighting can be achieved by using window types A, C and D compared to the base case. However, the selection of the most energy-efficient window strategy is not possible without considering the overall energy benefits that a window can provide for the building, thus considering heating, cooling and lighting.

TOC

The result of the simulation for the total energy-saving by the application of different glazing types and systems are presented in Figure 4.7. The graph shows that a double-skin façade type with double-glazed clear glass for the inner pane and single-glazed clear glass for the outer pane (Type G) results in the highest energy-savings: by around 7.5%. However, by switching the position of two layers (Type H: double-glazed clear glass for the outer pane and single-glazed clear glass for the inner pane), less energy saved. The inner pane in air-conditioned DSF buildings is the place where the majority of heat transfer occurs due to higher temperature differences between the conditioned indoor space and unconditioned air in the cavity. Therefore, double-glazed pane with higher thermal insulation is better to be placed at the inner layer in order to reduce the radiative and convective heat transfer into the building. Considerable differences in energy-saving can be found between using clear glass and tinted glass. In temperate climates with high heating degree days (HDDs) clear glass allows for relatively easy transmission of both heat and light into a building, thus reducing the energy need for heating and lighting. For this reason, single-glazed clear glass even performed better than the reference design: a DSF with two layers of 10 mm glass (outer: tinted; inner: clear) and 95 cm air cavity in between.

These results were obtained for a high-rise case-building with North-East and South-West façade fully glazed and with high infiltration rate and no additional thermal insulation. Changing the orientation of the windows may influence the energy-savings of the glazing types in a different way. However, the aim of this study is to assess envelope strategies for the existing building and therefore the orientation of building was not changed.

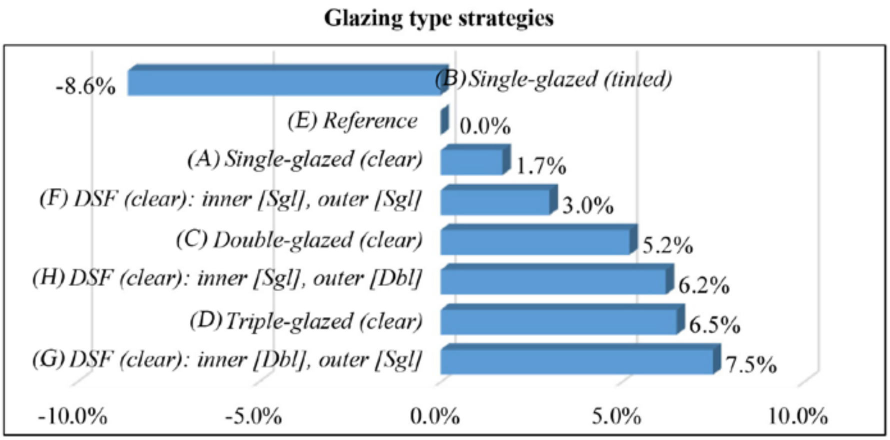

FIGURE 4.7 The effect of using different glazing type on the percentage of total energy-saving.

§ 4.4.2 Window-to-wall ratio

The effect of window size on building energy consumption is investigated for different values of window-to-wall ratio (WWR). The North-East and South-West facing façades of the EWI building are fully glazed, while the other facades are made from 1 m of reinforced concrete and are designed to carry the lateral loads. In order to test the impact of window size, the outer pane of the DSF is subjected to modification while the inner pane is kept unchanged. While a WWR of 100% represents the reference design, three other values (80%, 50% and 30%) were also simulated. Except the reference model that is fully glazed, for other values of WWR the external wall that replaces the glass is supposed to be uninsulated similar to the roof conditions at this building. Therefore, the opaque part of the façade is considered to be made from 20 cm brick wall with no insulation (U-value = 2.22 W/m²K).

WWR	Annual heating demand			Annual cooling demand			Annual lighting demand		
	Total heating (kWh)	Heating / conditioned area (kWh/m²)	Percentile difference (%)	Total cooling (kWh)	Cooling / conditioned area (kWh/m²)	Percentile difference (%)	Total lighting (kWh)	Lighting / conditioned area (kWh/m²)	Percentile difference (%)
30%	4040547	224.6	0.5%	154228	8.6	20.9%	658280	36.6	-5.5%
50%	4043043	224.8	0.5%	165214	9.2	15.3%	646698	35.9	-3.8%
80%	4057811	225.6	0.5%	182546	10.1	6.4%	630553	35.0	-1.3%
100% ®	4062323	225.9	----	195051	10.8	----	622062	34.6	----

TABLE 4.4 Simulation results obtained for different window-to-wall ratio.

The simulation results showed that for lower values of WWR, a higher percentage of energy-saving is achieved for both cooling and heating; meanwhile, energy use for electric lighting increased slightly compared to a fully glazed façade. In absolute values the differences were not significant. Since the external wall that replaces the glass has no thermal insulation and heating is the dominant type of energy consumed in this climate, replacing the glazed area with an uninsulated opaque façade element has limited energy benefits for the building. When the external wall that replaces the glass is not insulated, the maximum saving of total energy consumption is around 0.4%. Generally, a lower WWR is more beneficial in reducing the heat transmission through the glazed area but on the other hand limits daylight penetration and solar heat gains in winter. However, transmissions seem to be the more important factor in this case.

TOC

For the next step, the effect of different values of WWR were simulated again by improving the thermal insulation properties of the external wall that replaces the glass. For a well-insulated external wall (U-value = 0.25 W/m^{2}K), the maximum energy-saving improved to about 2.8% for a WWR of 30%. Increasing the WWR to 50% and 80%, resulted in a lower energy-saving of about 2.1% and 0.7% respectively.

As mentioned previously, a single-glazed tinted window has lower energy performance than a double-glazed clear glass window. The last modification to the existing facade was, therefore, performed by replacing the glazing type to type G from the previous section, which had the best thermal performance, while keeping the external wall well-insulated. Surprisingly, high (100%) or low (30%) values for WWR lead to less energy-saving. This means that for a high-performance envelope (low U-values for opaque parts and for glazing) on office buildings in a heating dominant climate, energy-saving is highest when the WWR is around 50%, which is the right balance for reducing heat transmission and increasing solar heat gains in winter. Generally, our findings are in good agreement with the result of Ochoa et al. (2012). They found the optimum WWR for East and West orientated windows (double-pane clear glass) between 50-60% for a hypothetical office room in a temperate climate.

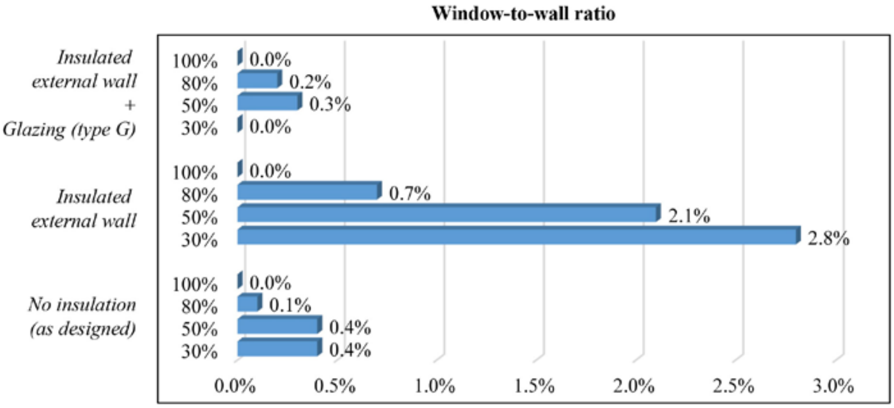

FIGURE 4.8 The effect of different WWRs (Y-axis) on the percentage of total energy-saving presented in three scenarios.

§ 4.4.3 Shading

The admittance of daylight and solar radiation has quite a significant influence on the energy consumption of buildings with a high percentage of window-to-wall ratio. Appropriate shading can play an important role for saving energy for cooling the building in summer. In order to have a high-performance shading strategy, it is important to provide a balance between easy access to view and daylight from one side and heat gain or glare control from the other side. Shading can be achieved by a wide range of building components including interior or exterior elements such as blinds, louvers, overhangs, side fins, and balconies. Another way to control sunlight without using blinds or external shading devices is the application of electrochromic glazing (switchable glass). Electrochromic glazing is an electronically tintable glass that can control glare and overheating.

Simulation results for 8 shading strategies (including the reference design) and a scenario with no shading device is presented in Table 4.5. During the winter, from a thermal standpoint, shading might be unfavourable. In climates where the dominant energy usage is heating, winter radiation entering through the windows can contribute to passive solar heating positively. It can be seen from the simulation results that no shading is the best option with 2.8% saving of total energy use compared to the reference case. No shading allows easy transmittance of light and solar energy into the building which leads to around 28% saving on electric lighting besides 0.5% saving on heating energy. All the other shading strategies negatively affect the heating demand of the building.

Generally, switchable and adjustable shading devices showed better performance compared to fixed external sun-shading strategies, since the operation of them is set based on the occupancy schedule and the solar radiation intensity. It means that shading operation is on when the building is occupied (7:00 am to 19:00 pm) and the direct solar irradiance exceeds a threshold value of 120 (W/m2). Electrochromic glazing has the second best overall energy performance among the shading strategies with considerable energy-savings for lighting (16.9%) and cooling (11.3%) and a total energy-saving of around 1%. Shading the envelope with 1 m of projected overhangs can slightly improve the energy consumption (0.3%), but in combination with electrochromic glazing, the effect was negative, reducing the performance from 1% to 0.5%.

SHADING	Annual heating demand			Annual cooling demand			Annual lighting demand		
	Total heating (kWh)	Heating / conditioned area (kWh/m²)	Percentile difference (%)	Total cooling (kWh)	Cooling / conditioned area (kWh/m²)	Percentile difference (%)	Total lighting (kWh)	Lighting / conditioned area (kWh/m²)	Percentile difference (%)
S.1	4041478	224.7	0.5%	210467	11.7	-7.3%	448354	24.9	27.9%
S.2	4092286	227.5	-0.7%	179003	9.9	8.2%	589073	32.7	5.3%
S.3	4122161	229.2	-1.4%	171848	9.5	11.9%	594102	33.0	4.5%
S.4	4174134	232.1	-2.7%	154634	8.6	20.7%	610293	33.9	1.9%
S.5 ®	4062323	225.9	----	195051	10.8	----	622062	34.6	----
S.6	4176592	232.2	-2.7%	134027	7.4	31.3%	555235	30.9	10.7%
S.7	4079531	226.8	-0.4%	188654	10.5	3.3%	634727	35.3	-0.2%
S.8	4124334	229.3	-1.5%	172986	9.6	11.3%	516679	28.7	16.9%
S.9	4153924	230.9	-2.2%	160103	8.9	17.9%	533717	29.7	14.2%

S.1 Without shading; S.2 Overhang (1m); S.3 Overhang+side fins (1m); S.4 Louver+overhang+side fins (1m); S.5 Reference: Blind (inside the cavity); S.6 Blind (outside); S.7 Balcony (2m)+blind (inside); S.8 Electrochromic glazing; S.9 Electrochromic glazing+overhang (1m)

TABLE 4.5 Simulation results obtained for different shading strategies.

For two shading strategies, blinds with medium reflectivity slats are adjusted within 5 cm distance from the outer pane. The angle of the blind slat is set on 45° and the operation of them is set based on the occupancy schedule. Locating the blinds inside the DSF cavity lets heat being transmitted into the cavity but the blinds might cut-off daylight penetration into the interior. For this reason, relocating the blinds to the outside (with the same distance from the outer pane) slightly reduces the overall energy consumption by 0.2%. The results show that for lighting and cooling, placing the blinds outside can save more energy than placing them inside the cavity, but in regard to heating indoor blinds are a better solution. Finally, integrated external shading strategies by the application of louvers, overhangs, balconies or side fins have a negative impact, i.e. they increased the total energy consumption by 0.1% to 0.8%.

The important role of the DSF cavity (95 cm) in providing a constant shading for the building interior should be emphasised here. Surprisingly, when there was no shading selected, cooling demand just slightly increased by about 7.3%. Furthermore, selection of a single-glazed tinted glass as outer glass pane (reference design) limited solar radiation transmittance into the building interior. Therefore, a deep cavity in combination with tinted glass simultaneously limit the solar heat gain into the EWI building even when there is no shading device present. Therefore, changing the glazing type might influence the performance of the shading devices.

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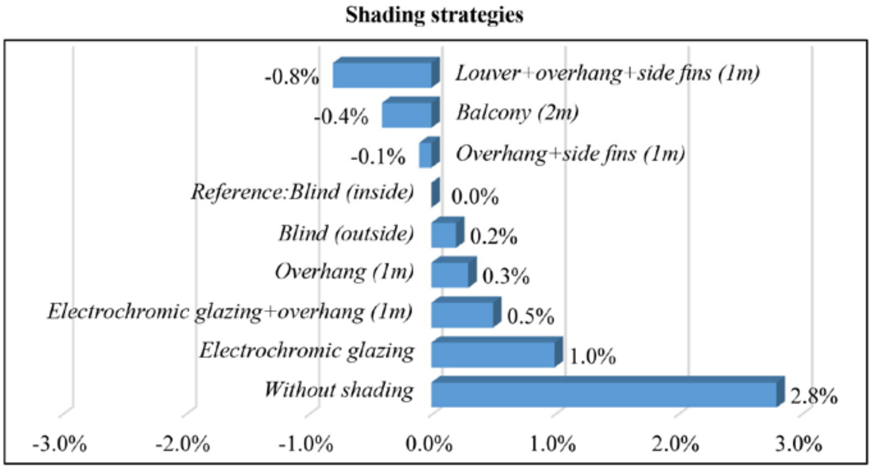

FIGURE 4.9 The effect of shading strategies on the percentage of total energy-saving.

For the next step, therefore, the type G glazing from the previous section is selected for the base case and the impact of different shading strategies re-simulated, the results are shown in Figure 4.10. The results of these simulations for a high-performance double-skin façade showed less energy benefits coming from using shading devices. For the majority of shading strategies, the negative effect of shading during the heating period is higher than the positive effect during the cooling period. Shading strategies like blinds (outside), electrochromic glazing and integrated external shadings increased the heating load more than other strategies. In case of outdoor blinds, despite 4.9 kWh/m^2 of energy-saving for cooling and 7.6 kWh/m^2 for electric lighting, a considerable increase of the heating load (11.1 kWh/m^2) reduces the overall energy benefits to about a mere 0.4%. However, when there is no shading system in place, energy-saving increased by 4.3%. Despite the positive energy benefits achieved through removing a shading device, the excessive amount of daylight may affect discomfort glare for the occupants. This often leads to increased dissatisfaction especially for the period of high solar radiation intensity. Changing the shading operation schedule to only operate in summer, not only can avoid glare but it might provide saving of cooling energy without increasing the heating demand in winter.

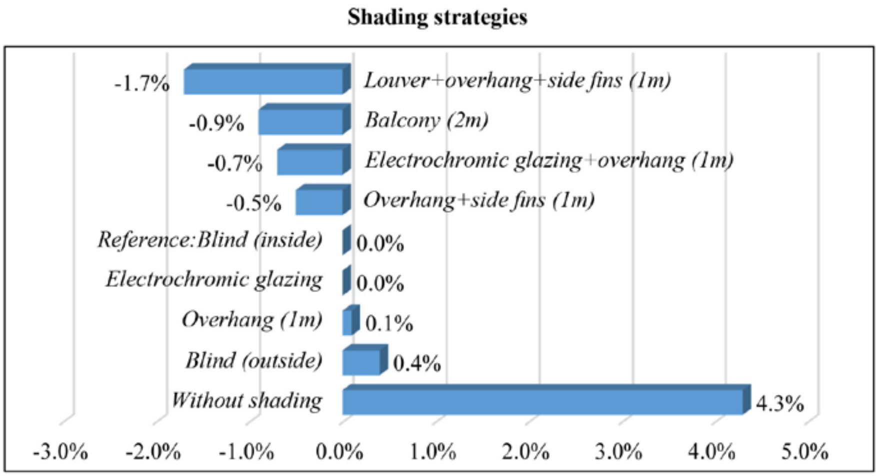

FIGURE 4.10 The effect of shading strategies with a high-performance window (type G) on the percentage of total energy-saving.

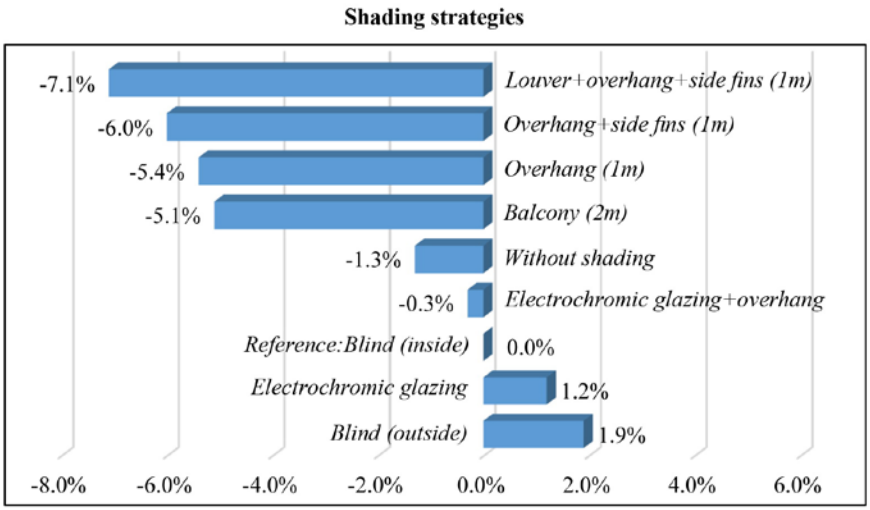

FIGURE 4.11 The effect of shading strategies when the operation schedule only includes summer use on the percentage of total energy-saving (with glazing type G).

Therefore, a summer operation schedule is set for all adjustable shading strategies and the impact of different shading strategies re-simulated with keeping the type G glazing, the results are shown in Figure 4.11. When the operation schedule only includes summer use, the energy benefits coming from using adjustable shading devices are quite different. The results showed using outdoor blinds is the best shading solution led to an overall energy-saving by about 1.9%, followed by electrochromic glazing ranked as the second best with 1.2% energy-saving. When there is no shading system in place, more cooling energy is needed in comparison with the reference case that caused the overall energy to be increased by 1.3%. Finally, the fixed external shading strategies showed considerably a lower energy performance compared to the adjustable shading strategies.

§ 4.4.4 Roof

In high-rise buildings, compared to the vertical surfaces, only a small percentage of the building envelope is allocated to the roof. The EWI building is no exception but due to a big 2-storey attachment, the roof surface is relatively a bit larger. Since the building has no thermal insulation, a green roof might reduce the energy consumption of the building by among others adding thermal mass to the roof. The evaporative cooling effect of a green roof may be beneficial in summer but detrimental in winter. The whole roof area is therefore covered by an extensive green roof and the energy usage prior and after the application of green roof is simulated. The properties of the simulated green roof are described in Table 4.6.

GREEN ROOF PARAMETER	VALUE
Leaf area index (LAI)	5
Height of plants (m)	0.1
Leaf reflectivity	0.22
Leaf emissivity	0.95
Minimal stomatal resistance (s/m)	180

TABLE 4.6 Green roof properties.

The results of the simulation showed that a 10 cm green roof can provide some energy-saving for cooling and for heating by around 1.6% and 1% respectively. In comparison with a green roof a well-insulated roof (U-value: 0.15 W/m^2-K) resulted in greater overall energy-savings. Adding a green roof to a well-insulated roof hardly influences heating energy consumption, showing just a reduction in cooling energy consumption by 0.1%.

ROOF	Annual heating demand			Annual cooling demand			Annual lighting demand		
	Total heating (kWh)	Heating / conditioned area (kWh/m^2)	Percentile difference (%)	Total cooling (kWh)	Cooling / conditioned area (kWh/m^2)	Percentile difference (%)	Total lighting (kWh)	Lighting / conditioned area (kWh/m^2)	Percentile difference (%)
1	4069714	226.3	1.0%	194115	10.8	1.6%	622568	34.6	0.0%
2	3970393	220.7	3.4%	196226	10.9	0.5%	622568	34.6	0.0%
3	3972018	220.8	3.4%	196537	10.9	0.4%	622568	34.6	0.0%
4 ®	4110193	228.5	----	197376	11.0	----	622568	34.6	----

1. Green roof (uninsulated roof); 2. Green roof (well-insulated roof); 3. Well-insulated roof; 4. Reference (no insulation).

TABLE 4.7 Simulation results obtained for roof strategies.

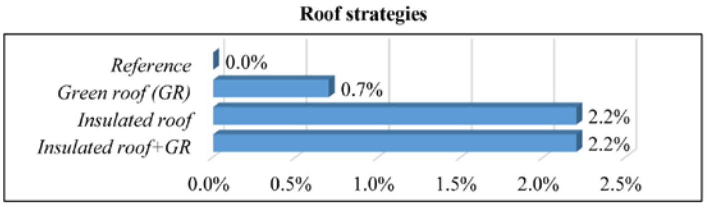

FIGURE 4.12 The effect of roof strategies on the percentage of total energy-saving.

§ 4.4.5 Integration of envelope strategies

According to the results obtained from the previous analyses, an integrated design solution was defined. The final combination for the design of the envelope was selected based on the strategies that provided the highest energy benefits for the building. As a result, this combination might not correspond to an economically feasible envelope design for refurbishment of an existing building but it is expected to have a high energy-saving potential. In Table 4.8 the final combination of building parameters and their relevant values for the integrated strategy are listed accordingly.

Glazing type	DSF: inner pane: [Dbl: Clr 6mm/6mm air/6mm] - outer pane: [Sgl: Clr 10mm]
Window-to-wall ratio	50%
Shading strategy	Blinds (outside) with summer operation schedule
External wall insulation	0.25 W/m²K
Roof insulation	0.15 W/m²K
Infiltration rate	0.7 ac/h

TABLE 4.8 The final combination of building envelope parameters.

Comparing the results of the high-performance integrated design to the reference design, shows that the differences are quite significant. The combination of energy-saving measures reduces the total energy consumption by 42%, the heating demand by 64% and the energy use for electric lighting by 34%. However, replacing the tinted glass pane with a clear glass and lowering the amount of air infiltration resulted in a 40% increase of the cooling load. In terms of cooling load, although the differences are big in percentage, they are small in absolute value (6.8 kWh/m²). As the cooling energy demand is very limited compared to heating energy demand, this small increase does not have a significant effect on the total energy consumption and can be neglected. However, it is important to be aware of overheating inside the offices.

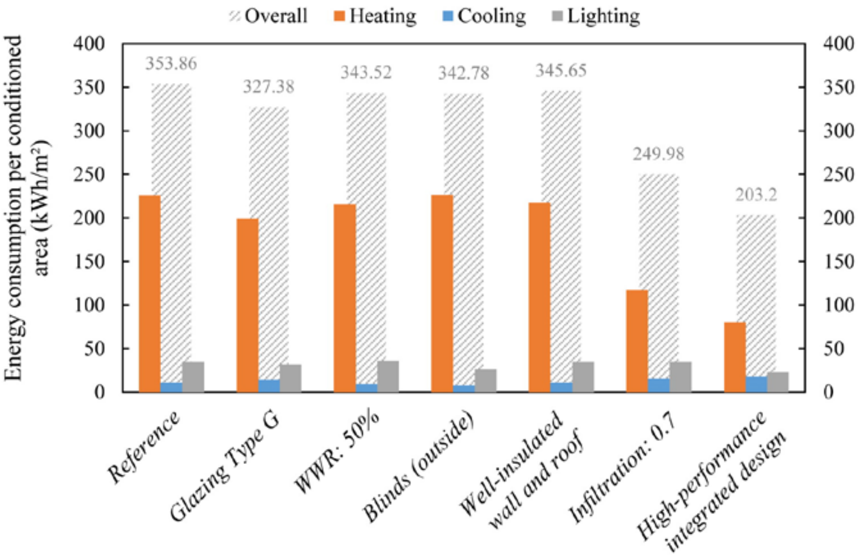

FIGURE 4.13 Comparative energy analyses of the selected design options and the reference design.

§ 4.5 Conclusion

In temperate climates, the effect of envelope parameters on building energy consumption was assessed for an existing high-rise office building. Energy simulations in line with a sensitivity analysis defined 4 façade parameters with higher impact on building energy consumption; hence need more consideration for improvement. These measures were: glazing type, window-to-wall ratio, shading and roof strategies.

A large number of computer simulations were run to evaluate the energy-saving potential of various design variables, as well as their combinations. The main findings of this study are outlined as follows:

- Considering the glazing type, we found that a DSF type with double-glazed clear glass for the inner pane and single-glazed clear glass for the outer pane results in the highest energy-savings.
- For a high-performance envelope (low U-values for opaque parts and for glazing), energy-saving is highest when the WWR is around 50%, which is the right balance for reducing heat transmission and increasing solar heat gains in winter.
- For heating-dominant climates in which passive heat gains are highly desired, adjustable shading strategies such as operable blinds and electrochromic glazing perform considerably better than fixed external shadings if a summer operation schedule set.
- In buildings with a DSF, for lighting and cooling, placing the blinds outside can save more energy than placing them inside the cavity, but in regard to heating indoor blinds perform slightly better.
- For a non-insulated roof, a 10 cm green roof can provide an overall energy-saving by around 0.7%. However, adding a green roof to a well-insulated roof hardly influences energy consumption.
- Finally, the integration of high-performance design solutions offers a considerable saving in energy by around 42%, 64%, and 34% for total energy, heating energy and electric lighting energy use respectively.

Energy-saving strategies for existing buildings are different from new buildings in that many of the design variables are fixed such as the building orientation. One of the limitations of this study, therefore, is that it does not provide energy simulations for all possible orientations. The main facades of the case building have an East respectively West orientation that is part of the boundary conditions in this research. However, our findings could provide a clear idea and a better understanding of the influential envelope design measures for energy consumption reduction of high-rise office buildings and their effect on cooling, heating and electric lighting in temperate climates.

TOC

Differences in specifications such as the building's properties beside the indoor condition settings are important parameters that define the performance and, thus, the effectiveness of design strategies. As a consequent, uncertainties related to simulation inputs are important to be considered prior to finalising the base model. In order to cope with uncertainties related to model inputs, a sensitivity analysis (SA), thus, is recommended to be carried out in line with energy simulations. This method helps to have a better understanding of the relevant variables and their degree of influence on the building's energy consumption.

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PART B / TROPICAL CLIMATE

§ 4.6 Tropical climate: KOMTAR building

§ 4.6.1 Reference building description

The KOMTAR tower is a 65-storey commercial building that is located in George Town, Malaysia (Latitude 5°17´N and Longitude 100° 27´E). The building is located in the centre of a high-density urban area. This high-rise tower is considered as the main landmark for the Penang province. At the time of completion in 1986, it was the second tallest building in Asia. The KOMTAR building is a mixed-use tower, comprising administrative offices on top of a 4-storey podium that accommodates outlet retail and restaurants. The building has a twelve-sided plan shape that approximates a circle.

The KOMTAR building features an open-plan office layout that encloses a central service core (see Figure 4.14). Each floor has a total gross floor area of 2894 m^2. The service core that houses lift lobbies, stairways and sanitary spaces occupies about 22% of the total floor area. The plan depth is 16 m measured from central core to façade or 60 m from façade to façade. Except for the thick reinforced concrete floor slabs and the exposed columns, the remaining area of the external façade which is around 80% is covered with 6 mm single pane glass. The floor-to-floor height is about 3.5 m. Manually operated blinds are installed inside the building at close distance from the external façade in order to control glare and the amount of daylight inside offices. However, the application of indoor blinds can be a subject of debate as they reduce the view out, increase the need for artificial lighting and are less effective as sun shading. The building is equipped with a variable air volume (VAV) air supply system and an air-cooled chiller system that provides cooling for the entire office areas and part of the service core (corridors). Sanitary spaces only have mechanical ventilation without cooling.

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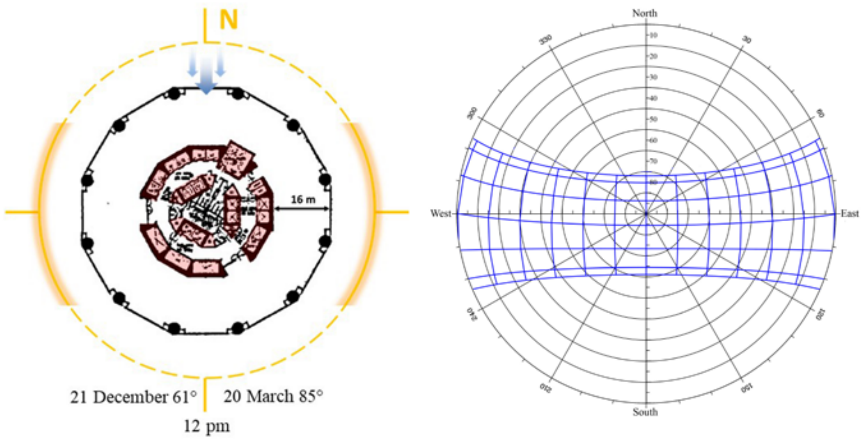

FIGURE 4.14 A typical office floor plan and the orientation of the building along the sun path for George Town.

§ 4.6.2 Climate data

Georgetown is the capital city of the Malaysian province Penang Island. It has the highest population density among all Malaysian cities. The city features a tropical climate (also known as an equatorial climate) with considerable amount of annual precipitation. The temperature is relatively constant throughout the course of the year. The mean monthly temperature for the warmest and coolest month is 27.2 °C and 28.8 °C, respectively (Figure 4.15). The average monthly wind speed varies in the range of 1.6 m/s to 2.7 m/s. Winds may blow from all directions but the predominant wind direction is North. The relative humidity typically fluctuates between 70-90%, except from late November through to March when humidity levels are slightly lower (Figure 4.16). Low latitudes (close to the equator) receive a relatively large amount of radiation all year, but a great extent of it is diffuse radiation due to haze and clouds. Detailed energy consumption data of the KOMTAR building were collected for the year 2004. For this reason, the performance of the building was simulated using 2004 weather data (US Department of Energy) from the nearby weather station at Penang Airport (20 km south-west of the location).

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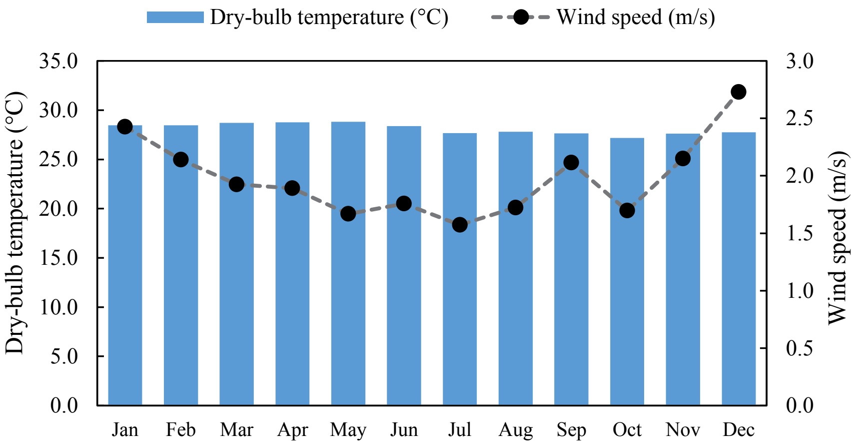

FIGURE 4.15 Mean monthly values of the dry-bulb temperature and wind speed in George Town for the year 2004.

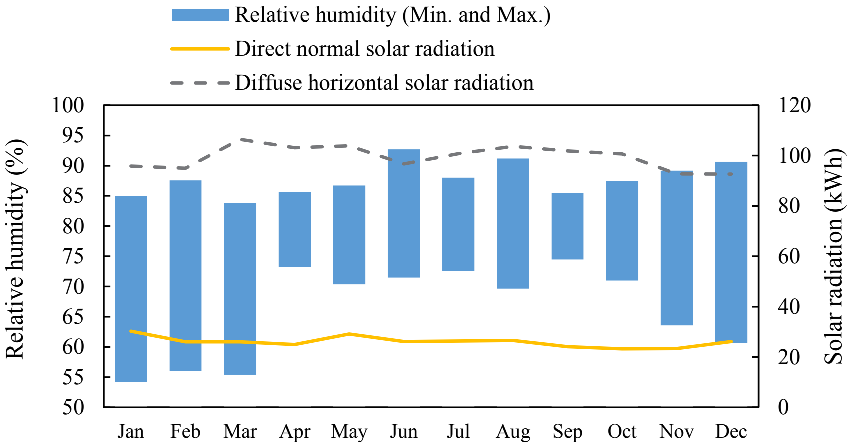

FIGURE 4.16 Mean monthly values of relative humidity (minimum and maximum) and solar radiation in George Town for the year 2004.

§ 4.6.3 Simulated building model

The DesignBuilder interface version 4.7 was used to create the model of the KOMTAR building (see Figure 4.17). The real building properties and real climate data were used for making the simulation model. The construction properties used in this model are summarised in Table 4.9. With regards to uncertain input parameters, different quantities of inputs were simulated and the variation was observed. The result of this sensitivity analysis (SA) is presented in Table 4.10. This analysis showed that cooling and electric lighting loads are highly responsive to changes in the shading system (71.29 kWh/m^2) so this should have the first priority for energy saving. Building operation details and occupancy-related parameters such as occupancy density (the number of people per square meter of occupied area), occupancy rate (the ratio between the number of floors occupied divided by the number of total floors) and occupancy schedule (office hours) have considerable impact on the total energy use. Therefore, it is important to consider their effect for the validation of the simulated model. On the other hand, the effect of some parameters such as the insulation properties of external walls and roof, and their solar absorbance were found to be negligible (0.13-1.08 kWh/m^2) due to the relative small area of the opaque building envelope in comparison with the transparent area.

FIGURE 4.17 3D model of the KOMTAR building developed in DesignBuilder.

External wall	30 cm precast concrete
Roof	Uninsulated flat roof: asphalt 1 cm, concrete 10 cm, plaster board 1.3 cm
Partitions	Lightweight 2 × 0.25 cm gypsum plaster board with 10 cm cavity
Glazing type	Single pane clear (6 mm)
Window frame	Aluminium window frame
Shading	Indoor blinds with low reflectivity slats
HVAC system	VAV, air-cooled chiller

TABLE 4.9 Construction details of existing building.

BUILDING PARAMETER	Unit	Values	Max. output variation (kWh/m^2)
Infiltration rate	ac/h	0.7, 1*, 1.5	32.00
External wall insulation, U-value	W/m^{2}K	0.25^a, 0.35^b, 2.05^{c,} *	1.08
Roof insulation, U-value	W/m^{2}K	0.25^a, 0.37^b, 2.13^{c,} *	0.13
Cooling set point temperature	°C	24, 24.5*, 25	17.59
Occupancy density	people/m^2	0.05, 0.07, 0.1*	37.29
Occupancy schedule	---	weekends (open, close*)	26.27
Minimum outside fresh air	l/s- person	6, 8, 10*	22.7
Office equipment gain	W/m^2	8, 10*, 12	18.88
Glazing type	---	clear*, reflective, tinted	6.37
Exterior wall's solar absorptance	---	0.3 (Aluminium coating), 0.6 (concrete)*	0.20
Shading	---	no shading, indoor blinds*	71.29
Lighting target illuminance	lux	400*, 500	18.38

** The base case settings of the reference model that led to the validated model; a best practice building; b energy code standard; c reference building (uninsulated).*

TABLE 4.10 Sensitivity analysis of building parameters.

§ 4.6.4 Calibration of the model

The simulated model of the building was calibrated through a comparison of the measured and simulated energy use intensity (EUI) of the KOMTAR building for the year 2004. The energy figures presented in this paper are site energy in kWh/m^2 of gross floor area. The measured data were collected from the study done by Ismail (Ismail, 2007). The exact occupancy rate of the KOMTAR Tower at the time of data collection in 2004 is not available; therefore, the energy use intensity was calculated by dividing the site energy use (kWh) by the entire gross floor space (m^2), assuming that all floors were occupied at the time of data collection in 2004. Figure 4.18 presents the comparison between the monthly measured and simulated data. According to this figure, the absolute value of the percentile difference of simulated data deviates by more than 15% from the measured data if we assume 100% occupancy rate.

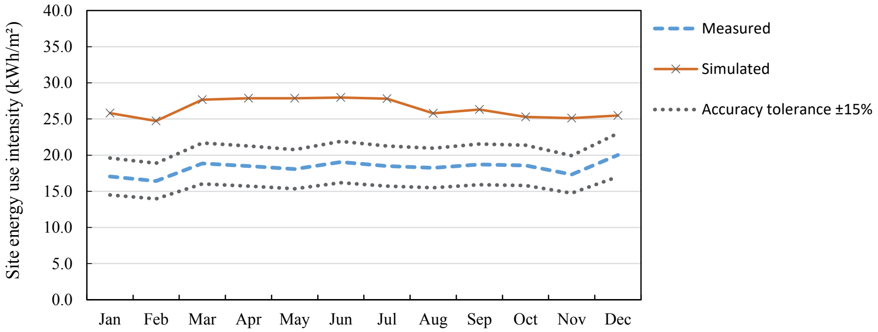

FIGURE 4.18 A comparison of simulated and measured data considering the total energy consumption of the KOMTAR building for the year 2004.

However, a report of the real estate market of the city of George Town shows an average occupancy rate close to 70% for office buildings in the year 2004 (Knight Frank, 2008) (p. 12). Therefore, the measured EUI was recalculated using different occupancy rates (40%, 60%, 80% and 100%) as shown in Figure 4.19. Diving the total energy consumed by the KOMTAR building in 2004 by a smaller floor area of the building (excluding unoccupied floors) can result in higher EUI. A comparison of the results for different occupancy rates show that the simulated data are acceptably close to the measured data when excluding about 30% of the gross floor area from the calculation of the EUI which is in agreement with the reported average occupancy rate for Penang in 2004 (Knight Frank, 2008).

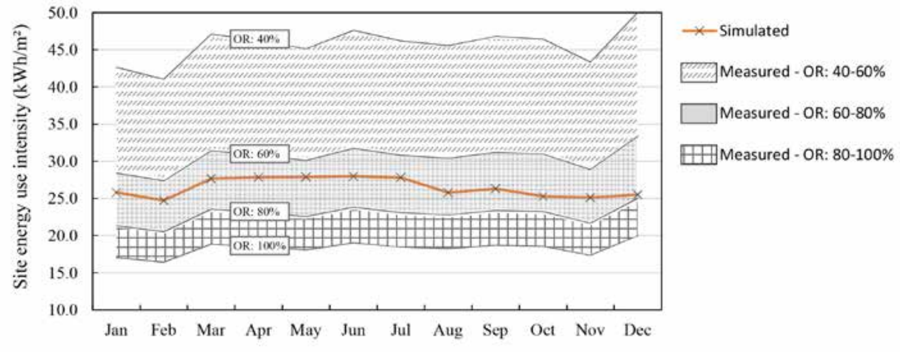

FIGURE 4.19 A comparison of simulated and measured energy use intensity for different occupancy rates for the KOMTAR building.

Using this model, a large number of computer simulations were run to evaluate the energy-saving potential of various design variables, as well as their combinations. As described in the following sections, retrofitting strategies for the building envelope grouped under 5 main categories were simulated using cooling, lighting and total energy use as the efficiency indicators.

§ 4.7 Results and discussion

The main objective of this study is to assess the role of building envelope design strategies on reducing the energy consumption of typical high-rise office buildings in tropical climates. For this purpose, the KOMTAR building was selected as a typical case building, and the energy usage pattern prior to and after the refurbishment was compared through a computer simulation. Through the simulations, the effect of each strategy was quantified as the percentage of reduction or increase in the total energy usage compared to the reference model. However, to have a better understanding of how retrofitting strategies can contribute to energy-saving, the effect of each strategy on cooling and lighting energy demand will be discussed additionally. In some cases, in order to apply a new strategy, there is a need to change the floor plan configuration, which means a different floor area of the conditioned space. In order to make different strategies comparable, the total energy consumption per conditioned area was used as an indicator.

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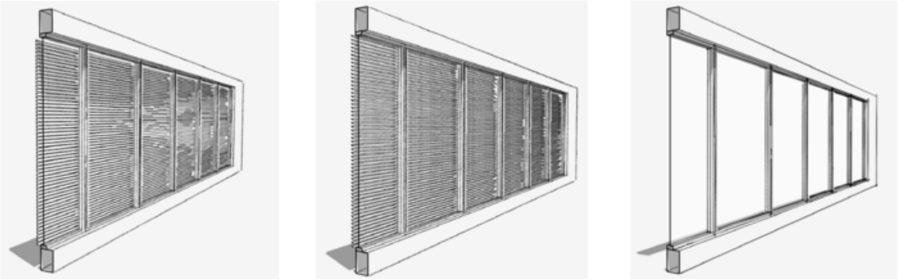
§ 4.7.1 Shading



S.1, S.2, S.3 & S.4
Blinds (slat angle: 5˚)

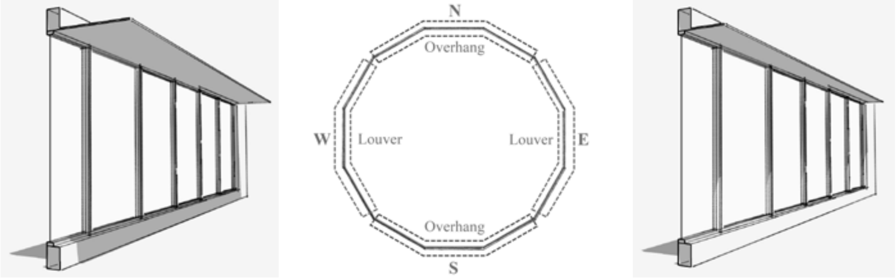
S.5
Blinds (slat angle: 45˚)

S.6
Without shading

S.7
Electrochromic glazing

S.8
Overhang 50 cm

S.9
Overhang 100 cm



Overhang 100 cm

S.10
Combined external shading devices

Louver 50 cm

FIGURE 4.20 A graphical illustration of the investigated shading strategies.

Shading devices (fixed or dynamic) are essential environmental controls to maintain thermal comfort inside the building and to reduce the energy consumption, especially in buildings with a large window-to-wall ratio. The performance of a shading strategy is highly influenced by the characteristics of the shading device (operation, material, slat angle, distance from external window, position relative to façade) and its orientation. In cities close to the equator, such as in George Town, the sun rises almost directly in the east, peaks nearly overhead, and sets in the west. North and south façades need fixed horizontal shades (such as overhangs) to cover high sun angles, whereas east or west facades require adjustable shades or higher coverage to block a wide range of sun angles. A graphical illustration of 10 shading strategies including the reference design and a scenario with no shading device is provided in Figure 4.20.

Shading strategies S.1-S.5 represent adjustable indoor blinds with different slat angles (5° and 45°), reflectivity (low or high) and control type (office hours or sun path). For the reference design (S.1), the operation of indoor blinds is set based on the occupancy schedule. It means that shading operation is on when the building is occupied between 8:00 to 17:00. For shading strategies S.3 and S.4, a new operation schedule according to the direction of the sun path throughout the course of the year in George Town and the occupancy hours was defined. In equatorial areas, the east and west elevations of a building receive significant solar radiation during the morning and evening hours, respectively. As a result, operating hours were set from 8:00 to 12:00 for the east-facing (45-135°), and from 12:00 to 17:00 for the west-facing (225-315°) indoor blinds, for every day of the year. North- (315-45°) and south-facing (135-225°) indoor blinds require to operate only for 6 months in a year but throughout the entire time the building is occupied; the former from 21 March to 21 September and the latter from 21 September to 21 March. For shading strategy S.5, the slats tilted at a 45° angle and the operation of indoor blinds is set based on the occupancy schedule. S.6 shows a scenario of no shading and for S.7 the single pane glass was replaced with an electrochromic glass of the same thickness. Three external shading strategies were also integrated into the external façade (S.8, S.9 and S.10). For each of these strategies, the energy consumption of the building is compared to that of the reference design as can be seen in Table 4.11 and Figure 4.21.

According to the simulation results, the lowest efficiency is related to the application of indoor blinds. Once the solar radiation is transmitted through the glass into the building part of it is reflected back towards the outdoor environment and part of it is absorbed by the blinds. The energy absorbed by the slats is then radiated as heat into the room. The heat trapped between the slats of the indoor blinds and the glass pane has an effect similar to an overheated cavity in a double skin façade (DSF), hence increases the adjacent indoor air temperature, particularly if low-reflectance slats and low-emissivity (low-e) glazing are used (Wilson, 2014). Our findings show that the inside surface temperature of a single 6 mm clear glass pane is between 5 to 20 °C (depending on the orientation) higher when indoor blinds are used (at 5 cm distance from the window with 5° slat angle (S.1)) than when no blinds are used (S.6).

TOC

SHADING TYPE	Annual cooling demand			Annual lighting demand			Annual total demand	
	Total cooling (kWh)	Cooling / conditioned area (kWh/m^2)	Percentile difference (%)	Total lighting (kWh)	Lighting / conditioned area (kWh/m^2)	Percentile difference (%)	Total energy consumption (kWh)	Total use / conditioned area (kWh/m^2)
S.1®	40,842,834	250.9	-	7,407,673	45.5	-	52,109,711	320.2
S.2	36,795,998	226.1	9.9%	6,962,667	42.8	6.0%	47,617,354	292.6
S.3	36,917,295	226.8	9.6%	2,913,120	17.9	60.7%	43,688,170	268.4
S.4	34,422,335	211.5	15.7%	2,733,509	16.8	63.1%	41,013,915	252.0
S.5	39,478,931	242.5	3.3%	5,687,472	34.9	23.2%	49,025,285	301.2
S.6	34,725,179	213.3	15.0%	1,922,753	11.8	74.0%	40,506,084	248.9
S.7	34,708,933	231.7	7.7%	4,053,337	27.1	40.5%	39,221,406	261.9
S.8	34,141,446	209.8	16.4%	1,930,704	11.9	73.9%	39,929,890	245.3
S.9	33,665,015	206.8	17.6%	1,952,780	12.0	73.6%	39,475,771	242.5
S.10	32,871,227	202.0	19.5%	2,200,138	13.5	70.3%	38,930,503	239.2

SHADING TYPE	Control type	Position	Slat width / projection (cm)	Distance to window (cm)	Slat angle
S.1. Blind (low reflectivity slat)	Office hours [a]	Internal	2.5	5	5°
S.2. Blind (high reflectivity slat)	Office hours [a]	Internal	2.5	5	5°
S.3. Blind (low reflectivity slat)	Sun path [b]	Internal	2.5	5	5°
S.4. Blind (high reflectivity slat)	Sun path [b]	Internal	2.5	5	5°
S.5. Blind (low reflectivity slat)	Office hours [a]	Internal	2.5	5	45°
S.6. Without shading	-	-	-	-	-
S.7. Electrochromic reflective 6mm	Solar 120 W/m^2	Internal	2.5	5	5°
S.8. Overhang	Fixed	External	50	0	0°
S.9. Overhang	Fixed	External	100	0	0°
S.10. Overhang + Louver	Fixed	External	Overhang: 100 Louver: 50	Overhang: 0 Louver: 10	Overhang: 0° Louver: 15°

CONTROL TYPE	SHADING DEVICE ORIENTATION	OPERATION SCHEDULE	
		Days	Hours
a Office hours	All orientations	1 Jan – 30 Dec	8:00– 17:00
b Sun path	North (315-45°)	21 Mar – 21 Sep	8:00– 17:00
	East (45-135°)	1 Jan – 30 Dec	8:00– 12:00
	South (135-225°)	1 Jan – 21 Mar and 21 Sep – 30 Dec	8:00– 17:00
	West (225-315°)	1 Jan – 30 Dec	12:00 -17:00

TABLE 4.11 Simulation results obtained for different shading strategies.

Changing the slat angle from 5o to 45° (S.5) results in more daylight access reducing the electric lighting demand. Replacing a low-reflectance slat with a high-reflectance one (S.2) can improve the total energy performance by 8.6%. Efficient shading operation can reduce energy use for electric lighting and for cooling as can be seen for shading strategies S.3 and S.4. Generally, the results indicate a superior energy performance for the case without indoor shading as compared to the case of indoor blinds. Using external shading strategies such as overhangs or louvers provides the best energy performance among all shading strategies. However, the energy saving is limited to 3.6-9.7 kWh/m² (as compared to S.6). Electrochromic reflective glazing also performed better than indoor blinds but leads to less energy saving than external shading devices. Among the indoor blind strategies S.4 has the best performance and therefore can be used when outdoor shading strategies is not applicable for high-rises.

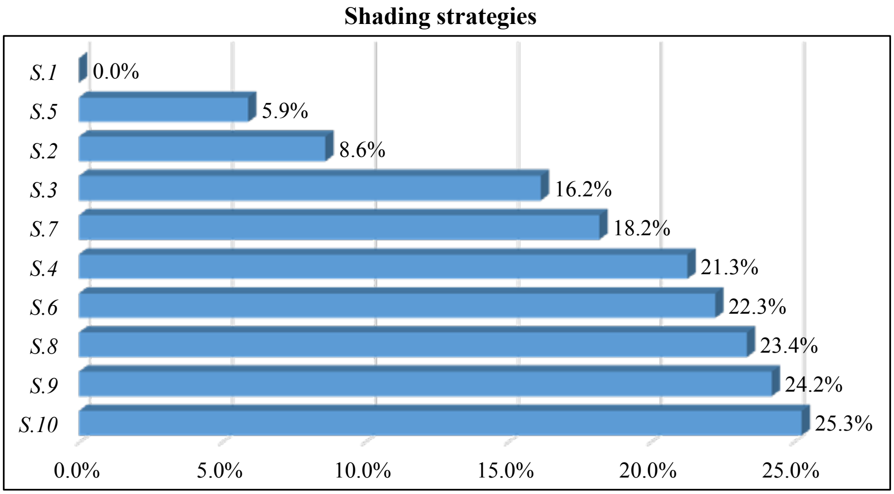


FIGURE 4.21 The effect of shading strategies on the percentage of total energy-saving.

§ 4.7.2 Glazing type

Following the selection of the shading system, the window is the second most important medium through which the extent of the admittance of sun radiation can be controlled. Glazing type and window-to-wall ratio (WWR) are the two important window characteristics that can reduce the incoming heat and the risk of overheating. Upon the selection of the glazing system, it is important to consider the potential impact of other design factors such as the effectiveness of shading devices, climate conditions (solar radiation and air temperature), and the building usage (commercial versus residential). In an office building, the occupancy is during the day and the use of as much daylight as possible is important. For climates that have high amounts of solar radiation, the solar heat gain coefficient (SHGC) of the glazing should be kept as low as possible, while a high light transmission coefficient can help to lessen electric lighting demand. Solar heat gain through windows is a major factor determining the cooling energy requirements of a building in tropical climates. The SHGC is the fraction of incident solar radiation that enters a building through the window. It is expressed as a dimensionless number between 0 and 1. A high SHGC indicates high heat gain, while a low value means low heat gain. Therefore, the selection of an appropriate type of glazing that can control both visual and thermal comfort is critical.

In the absence of a shading system, six glazing scenarios were investigated. Among these, one has a double skin façade (DSF) and the others have a single skin façade. The results of the breakdown of the total energy use into cooling and lighting and the percentage of total energy saving for the different glazing types are presented in Table 4.12 and Figure 4.22, respectively. It is found that spectrally-selective glazing (type C) is the most favourable option for office buildings that need high light levels and have a long cooling season. The results show up to 3.8% energy saving can be achieved by using glazing type C compared to 6 mm single pane clear glass (type A). Triple-glazing (type D) has a lower U value than spectrally selective glazing (type C) so that it has a higher resistance to heat flow. However, it has a higher SHGC and a lower light transmission which for tropical climates makes this glazing type less efficient than glazing type C. Additionally, it can be inferred that the impact of the U value of the glazing on the building's energy-efficiency is lower than the impact of the SHGC and the light transmission coefficient in tropical climate conditions. The savings by using triple-glazing is more than that of double-glazing; however, the difference is insignificant, so that the latter might be a more economical option.

The performance of reflective glazing (type E) and a DSF with 1.1 m cavity (type F) is considerably lower than of the reference design, increasing the energy consumption by 6.6% and 5.5% respectively. On the one hand, the SGHC of the reflective glazing is the lowest (0.23) among the glazing types; hence, the transmitted solar heat through the window is lower. On the other hand, the light transmission coefficient is also the lowest (0.18) so that a large portion of useful daylight cannot be transferred into the building. This will result in an increase of electric lighting demand to a value approximately 3 times that of the reference design. Accordingly, more cooling is also needed to compensate for the excessive internal gains by lighting. Apparently, the amount of cooling energy use that is needed to compensate excessive internal gains is higher than the amount of savings due to the less transmitted solar heat through the window; hence more cooling is needed for glazing type E compared to glazing types B, C and D. In the case of the DSF (type F), the cooling demand is slightly higher than of glazing type E, however the electric lighting use is lower.

GLAZING TYPE	Annual cooling demand			Annual lighting demand			Annual total demand	
	Total cooling (kWh)	Cooling / conditioned area (kWh/m^2)	Percentile difference (%)	Total lighting (kWh)	Lighting / conditioned area (kWh/m^2)	Percentile difference (%)	Total energy consumption (kWh)	Total use / conditioned area (kWh/m^2)
Type A®	34,725,179	213.3	----	1,922,753	11.8	----	40,506,084	248.9
Type B	33,701,197	207.1	2.9%	2,016,902	12.4	-4.9%	39,576,687	243.2
Type C	33,023,210	202.9	4.9%	2,073,412	12.7	-7.8%	38,954,918	239.3
Type D	33,377,269	205.1	3.9%	2,106,387	12.9	-9.6%	39,342,303	241.7
Type E	34,452,248	211.7	0.8%	4,853,625	29.8	-152.4%	43,164,061	265.2
Type F	31,949,926	213.3	0.0%	3,865,658	25.8	-118.5%	39,327,754	262.6

Glazing description	U-Value (W/m^2 K)	SHGC	Light transmission coefficient
Type A. [Sgl Clr 6mm]	5.78	0.82	0.88
Type B. [Dbl LoE (e2=0.1) Clr 6mm/13mm Arg]	1.49	0.57	0.74
Type C. [Dbl LoE Spec Sel Clr 6mm/13mm Arg]	1.34	0.42	0.68
Type D. [Trp LoE (e2=e5=0.1) Clr 3mm/13mm Arg]	0.78	0.47	0.66
Type E. [Dbl Ref-A-H Clr 6mm/13mm Arg]	2.23	0.23	0.18
Type F. DSF: inner pane: [Dbl LoE (e2=0.1) Clr 6mm/6mm Air] outer pane: [Sgl LoE (e2=0.2) Clr 6mm] – cavity depth: 1.1 m	1.18	0.45	0.63

TABLE 4.12 Simulation results obtained for different glazing type when no shading is employed.

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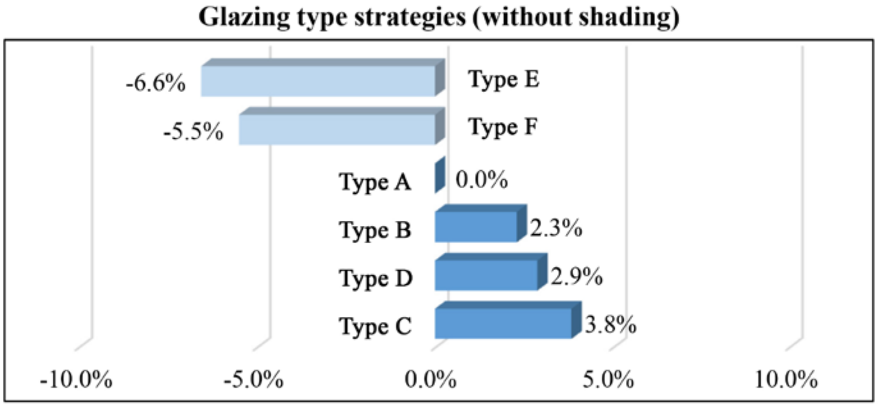


FIGURE 4.22 The effect of using different glazing type on the percentage of total energy-saving when no shading is employed.

As mentioned earlier, the effectiveness of shading is a major determinant in finding the optimal glazing type. For the next step, therefore, the most efficient shading strategy (S.10) from the previous section was selected for the base case and the impact of the different glazing systems was analysed. As shown in Figure 23, the integration of high-performance shading can reduce the potential energy savings from 3.8% to 1.0%, while the differences between the most and least efficient options can increase from 10.4% to 14.2%. As a result of that, spectrally selective glazing is still the most efficient option. When using a high-performance shading system, the percentile difference between single, double or triple pane windows is insignificant and reduces to less than 1%. The reason is because the exterior shading prevents a large part of solar radiation from reaching the glazing. Application of reflective glazing or a DSF can result in a considerable increase of energy consumption (specifically for electric lighting) and should be avoided. Interestingly, a double-glazed window slightly outperforms a triple-glazed one due to higher daylight transmission.

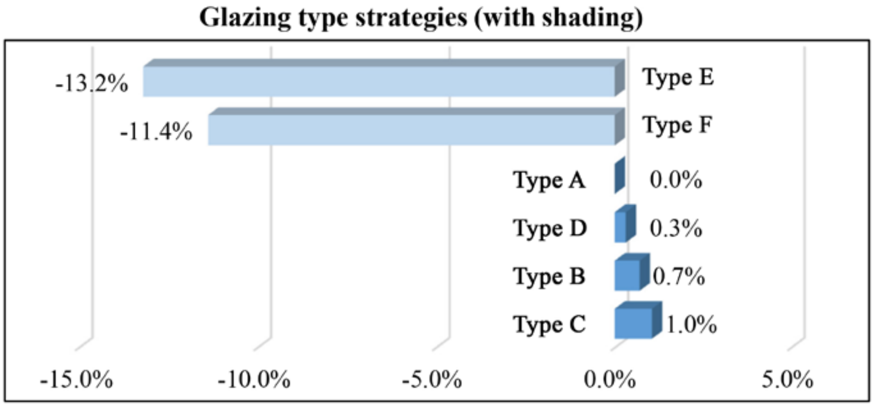


FIGURE 4.23 The effect of using different glazing types in combination with a high-performance shading strategy (S.10) on the percentage of total energy-saving.

§ 4.7.3 Window-to-wall ratio

When it concerns the value of rental property or the aesthetic quality and appearance of a high-rise building, it is evident that increasing the transparency and view out through applying large openings is more favourable. Additionally, the proximity of working stations to windows and access to view and daylight can improve office workers' health and productivity and reduces the need for artificial lighting. However, when it concerns the energy efficiency of buildings, particularly in tropical climates, a high WWR can increase the risk of overheating and raise the cooling demand. For each individual glazing type and shading system (or their combination), the optimal WWR might have a different range. Taking these factors into consideration, the aims are to investigate the optimal WWR for different glazing and shading systems and to define the most energy efficient solution.

From the previous section four glazing types that had a good energy performance were selected and window-to-wall ratios varying from 20% to 80% in steps of 20% (20%, 40%, 60%, and 80%) were analysed for energy efficiency. A WWR of 80% is the base design, or the WWR of the original KOMTAR tower. Values higher than 80% are not taken into account in this study because the remaining percentage of envelope area is composed of reinforced concrete floor slabs and exposed columns. Furthermore, values lower than 20% would not be desirable for the architectural design of office buildings and the occupant's wellbeing and were therefore not included in this study as well.

Moreover, two shading scenarios were investigated; no shading system (S.6), and a high-performance shading strategy (S.10). The results of the effect of different WWR on the total energy use for four different glazing types and two shading scenarios are presented in Figures 4.24 and 4.25. The values of the SHGC and the light transmission coefficients for the glazing systems are provided on the Y-axis on the right side of graphs.

In absence of a shading system, the glazing characteristics (such as SHGC and light transmission) have a dominant impact on the building's energy performance. In this regard, the glazing should have a low value of SHGC to attenuate the transmission of solar heat and a high value of the light transmission coefficient to admit as much daylight as possible. The results show that spectrally selective glazing (Type C) can reduce the total energy consumption more than other glazing types for almost all WWR values. Generally, the optimal WWR for improving daylight access and reducing heat gain is around 40% for all glazing types. Furthermore, the results show that for lower values of the WWR, such as 20%, only marginal differences exist between the most and least efficient glazing types (max. deviation = 5.1 kWh/m^2). However, for higher values of the WWR the extent of the deviation becomes larger and peaks at around 23.6 kWh/m^2 for a WWR of 80% (between glazing type C and A).

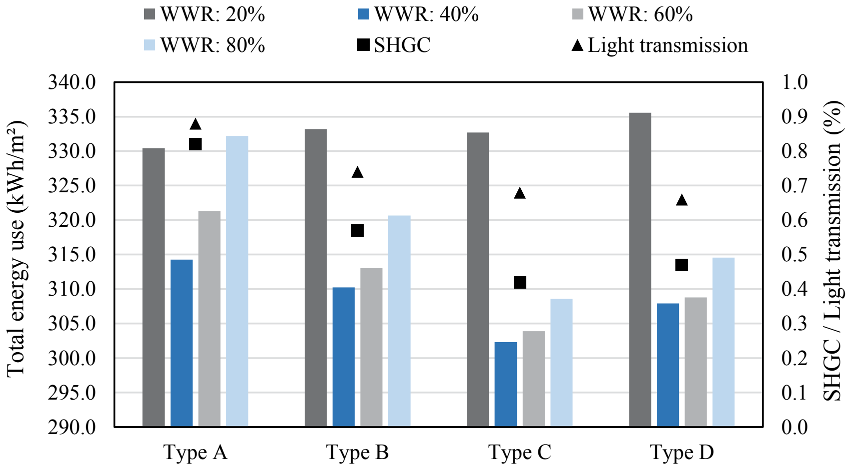


FIGURE 4.24 The effect of different WWRs on the total energy use for 4 different glazing types (X-axis) when no shading is employed (S.6).

With the use of a high-performance shading strategy (S.10), the higher the window-to-wall ratio goes, the lower the total energy use becomes (see Figure 4.24). A glazing type which lets a higher percentage of light to be transmitted through the glazing could result in higher energy saving, especially for lower values of WWR. For example, the single-pane clear glass (type A) slightly outperforms the other glazing types when the window-to-wall ratio is in a range between 20-60%. Increasing the ratio of the glazed area to 80% for glazing type A could result in a reduction of the electric lighting demand but at the same time in a considerable increase of solar radiation through glazing. The maximum energy saving can, therefore, be achieved by selecting glazing type C and a WWR of 80%, since it has the lowest SHGC and a better light transmission than glazing type D.

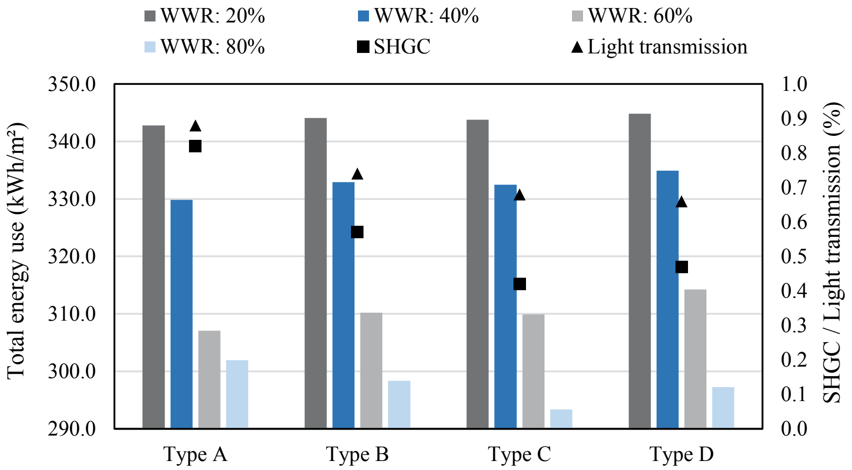


FIGURE 4.25 The effect of different WWRs on the total energy use for 4 different glazing types (X-axis) with the use of a high-performance shading strategy (S.10).

§ 4.7.4 Service core placement

Tall buildings are highly exposed to the full impact of wind and solar radiation. The use of buffer components such as service cores could have important effects on the building's energy performance, especially in tropical climates. In this regard, four different service core positions were considered, including a central core, a double-sided core (on the east and west sides) and two single-sided cores (either on the east or on the west side), as shown in Figure 4.26.

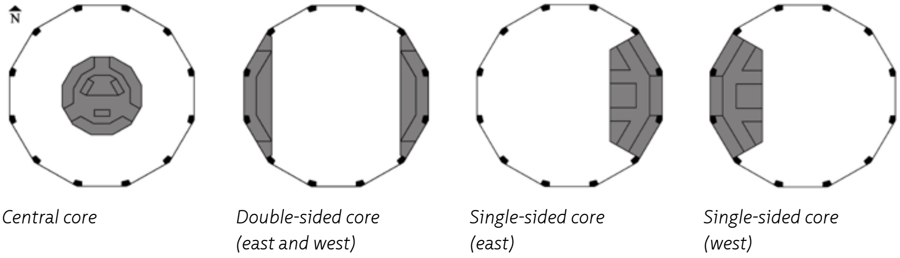


FIGURE 4.26 A graphical illustration of the investigated positions of the service core; service areas are presented in grey colour.

The service core encompasses three main zones (activities) including elevators, corridors and stairways, and sanitary spaces. For these zones, three HVAC templates were selected. Corridors and stairways are defined to have cooling and mechanical ventilation. The elevator zone is neither cooled nor ventilated; hence it is better to place it along the external walls. Finally, the sanitary facilities only require mechanical ventilation. The building's service core placement also determines which parts of the floor plan have openings. In this study, it is assumed that the external walls that are adjacent to the service areas have no openings/windows. In order to make the design options comparable, the total service core area and the proportional percentage of space allocated to each zone was kept constant.

The simulation results obtained for the different service core positions are shown in Table 4.13 when applying low-performance glazing (type A) and no shading system for the building envelope. The results show reductions in cooling loads in a range between 2.6% and 5.2% when the service areas are placed along the external façade rather than in the conventional central position as in the reference design. The service core can be placed on the east or west sides of the plan, or both, to serve as a buffer between the office areas and the outside to reduce the transmission of heat into the interior space through the external walls facing towards the excessive solar radiations.

While a peripheral location of a service core contributes effectively to reducing the cooling loads, it is important to consider the influence of increased electric lighting demand. Office areas that are located in the deeper parts of the floor plan receive less daylight and need therefore more energy to supply artificial light. Among the various service core configurations, a westerly positioned single-sided core results in the highest energy saving of about 2.4% (see Figure 4.27). Using a double-sided core on the east and the west sides reduces the cooling loads more than the other options but increases the electric lighting demand at the same time, resulting in less saving of total energy use. An easterly positioned single-sided service core can save up to 1.1% in total energy use as compared to the conventional central core layout.

SERVICE CORE PLACEMENT	Annual cooling demand			Annual lighting demand			Annual total demand	
	Total cooling (kWh)	Cooling / conditioned area (kWh/m²)	Percentile difference (%)	Total lighting (kWh)	Lighting / conditioned area (kWh/m²)	Percentile difference (%)	Total energy consumption (kWh)	Total use / conditioned area (kWh/m²)
Central®	34,725,179	213.3	-	1,922,753	11.8	-	40,506,084	248.9
Double-sided	32,942,516	202.2	5.2%	2,956,415	18.1	-53.6%	39,794,905	244.3
Single-sided (East)	34,038,502	207.8	2.6%	2,415,862	14.7	-24.8%	40,329,409	246.2
Single-sided (West)	33,637,332	205.3	3.7%	2,282,209	13.9	-17.9%	39,795,396	242.9

TABLE 4.13 Simulation results obtained for service core placement.

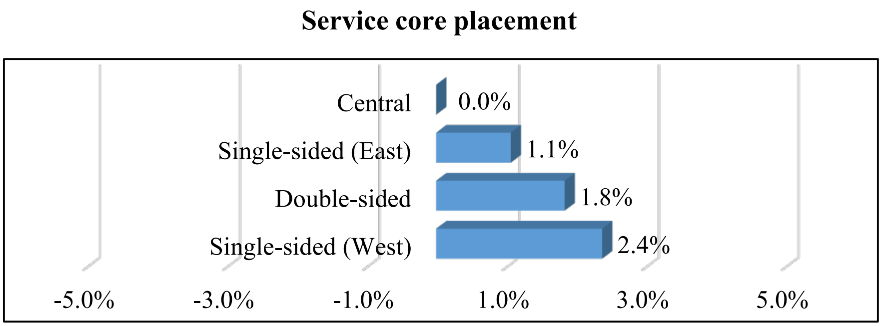


FIGURE 4.27 The effect of service core position on the percentage of total energy-saving with a low-performance envelope (no shading and 6 mm clear glass).

For the next step, the most efficient glazing type (C) and shading system (S.10) from the previous sections were selected for the base case and the impact of different service core positions was re-simulated, the results of which are shown in Figure 4.28. It turns out that a central core is more beneficial energy-wise when the building's façade is featured with a high-performance design. While the cooling energy use is almost equal for the different core positions, the differences in total energy use are mostly resulting from electricity usage for artificial lighting. Service cores that are located along the external façade have less openings, so that more artificial light should be supplied. In this regard, the most and least energy-efficient options for the service areas are a central and a double-sided core respectively.

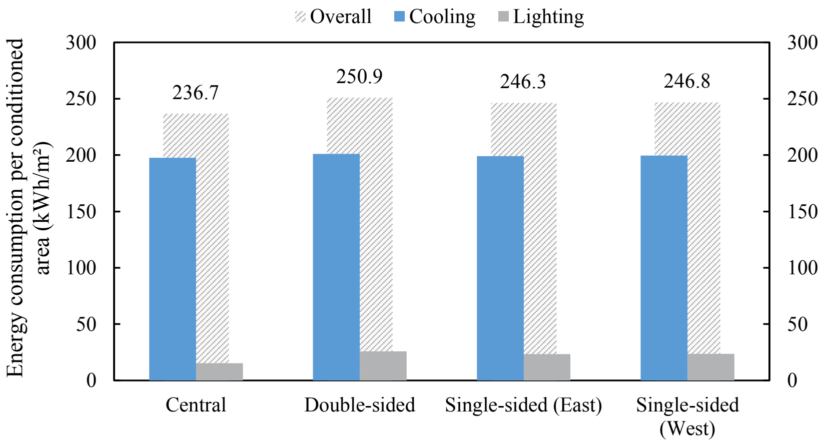
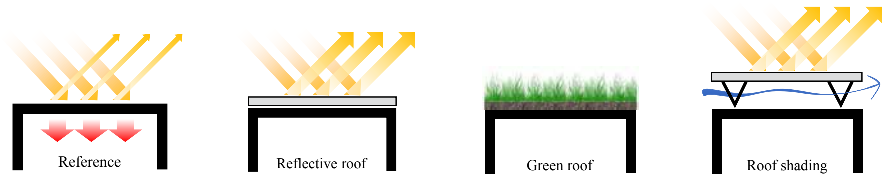


FIGURE 4.28 The effect of service core position on cooling, electric lighting and total energy use when having a high-performance envelope (external shading (S.10) and type C glazing).

§ 4.7.5 Roof

For the KOMTAR building, the roof makes up less than 4% of the total external surface area and therefore the effect of energy-saving strategies targeting the roof can be very small and limited mostly to the top floor. However, in order to protect the top floor from overheating, it is important to control solar heat transmission through the roof structure. A dark roof (reference design) can increase the surface temperature considerably as most of the solar radiation is absorbed by the roofing materials and then transferred as heat into the building. Three roof strategies, including a green roof, a reflective roof and roof shading, were compared to the reference design (dark bituminous layer; no thermal insulation) to find the extent of the energy saving and the most efficient design option. A graphical scheme of the design options and their properties is presented in Figure 4.29.



Outer surface: bituminous asphalt
U-Value (W/m2 K): 2.13
Solar absorbance: 0.85

Outer surface: vegetation
U-Value (W/m2 K): 1.45
Solar absorbance: 0.70
Leaf area index (LAI): 5
Height of plants (m): 0.1
Minimal stomatal resistance (s/m): 180

Outer surface: aluminium
U-Value (W/m2 K): 2.19
Solar absorbance: 0.30

Outer surface: aluminium
U-Value (W/m2 K): 2.19
Solar absorbance: 0.30
Distance from roof (m): 3.5

FIGURE 4.29 A graphical illustration of the investigated options for the roof designs along with their properties.

As a first step, the whole roof area was covered by an extensive 10 cm thick green roof with leaf area index of 5. The results of the simulation show that the shading and evapotranspiration effect of this green roof on the cooling load is not significant and that the total energy use is almost the same as of the reference design (see Table 4.14 and Figure 4.30). Covering the roof with high-reflective aluminium sheets can improve the building's energy performance up to 0.1%. Adding a shading structure made of high-reflective aluminium coating at 3.5 m distance above the roof can reduce the heat transfer more than the other roof strategies and leads to 0.2% energy saving for cooling and total energy use.

ROOF	Annual cooling demand			Annual lighting demand			Annual total demand	
	Total cooling (kWh)	Cooling / conditioned area (kWh/ m^2)	Percentile difference (%)	Total lighting (kWh)	Lighting / conditioned area (kWh/ m^2)	Percentile difference (%)	Total energy consumption (kWh)	Total use / conditioned area (kWh/ m^2)
Reference*	40,842,834	250.9	-	7,407,673	45.5	-	52,109,711	320.2
Green roof	40,818,574	250.8	0.0%	7,407,673	45.5	0.0%	52,085,296	320.0
Reflective roof	40,790,767	250.6	0.1%	7,407,673	45.5	0.0%	52,057,626	319.8
Roof shading	40,760,792	250.4	0.2%	7,407,673	45.5	0.0%	52,026,700	319.6

** uninsulated dark roof*

TABLE 4.14 Simulation results obtained for roof strategies.

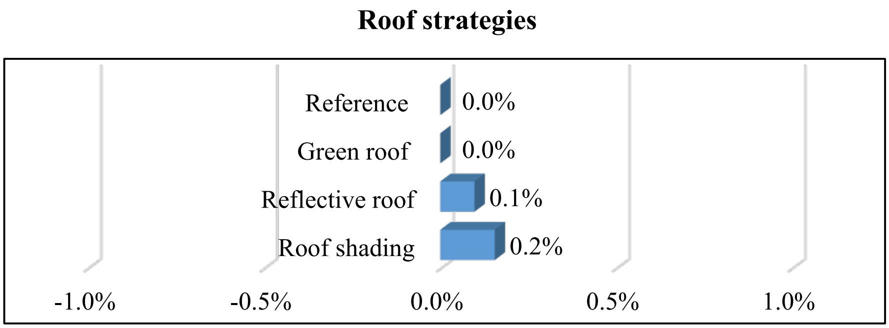


FIGURE 4.30 The effect of roof strategies on the percentage of total energy-saving.

§ 4.7.6 Integration of envelope strategies

According to the results obtained from the previous analyses, an integrated design solution was defined. The final combination for the design of the envelope was selected based on the strategies that provided the highest energy benefits for the building. In Table 4.15, the final combination of building parameters and their relevant values for the high-performance integrated design are listed. When using a high-performance shading and glazing system, two building envelope parameters were found to have a better performance if their design remain the same as reference building. These are the WWR and service core placement. According to the results of the sensitivity analysis, air infiltration can influence the building's energy performance to a large extent. Besides the five energy saving measures that were investigated earlier in this study, the integrated design has benefited from reduced air infiltration rate.

Shading strategy	S.10. [Combined external shading devices: Overhang + Louver]
Glazing type	Type C. [Dbl LoE Spec Sel Clr 6mm/13mm Arg]
Window-to-wall ratio	80%
Service core placement	Central service core
Roof type	Roof shading with aluminium coating
Infiltration rate	0.2 ac/h

TABLE 4.15 The final combination of building envelope parameters.

TOC

Comparing the results of the high-performance integrated design to the reference design shows that the differences are quite significant (see Figure 4.31). The combination of energy-saving measures reduces the total energy consumption by 36%, the cooling demand by 34% and the energy use for electric lighting by 66%. However, in terms of absolute values the differences are more significant for the cooling load (85 kWh/m^2) compared to electric lighting load (30 kWh/m^2). Shading was found to be the major determinant for selecting the optimal combination of envelope measures. Furthermore, air infiltration and glazing properties were found to be influential variables as well. Using shading type S.10 and glazing type C together can reduce the total energy consumption to around 236.7 kWh/m^2 as long as the position of the service core and the WWR are kept the same as of the reference design. The effect of roof shading is found to be negligible and only limited to the top floor.

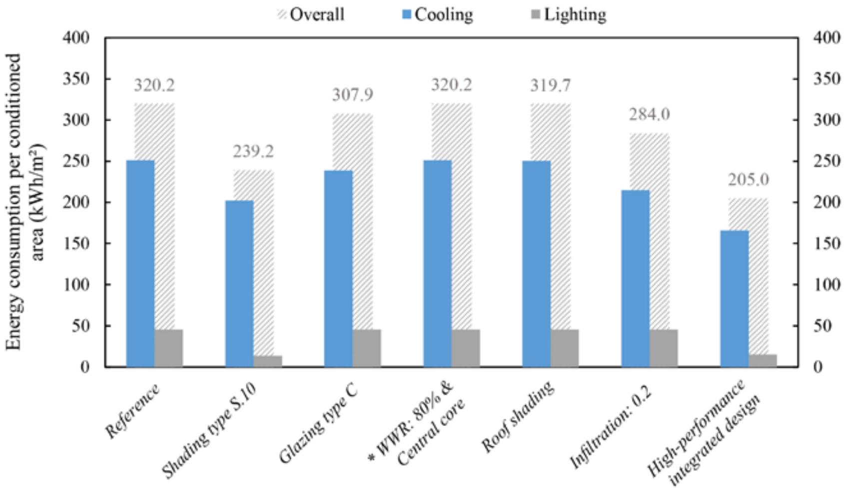


FIGURE 4.31 Comparative energy analyses of the selected design options and the reference design (*envelope parameters that remain the same as the reference design when employing shading type S.10 and glazing type C).

§ 4.8 Research limitations

One of the uncertainties of this study is related to the validation of the base model due to the absence of the exact occupancy rate of the KOMTAR Tower at the time of data collection in 2004. In order to cope with the uncertainties related to the occupancy rate, the measured energy use intensity was recalculated using different occupancy rates. The simulated data were in good agreement with the measured data for an occupancy rate of close to 70%. Furthermore, the results were in agreement with the reported average occupancy rate for George Town in 2004.

One of the limitations of this study is that the occupant's interaction with indoor blinds operation in the reference design was not taken into account. It means that blinds were at maximum coverage (slat angle of 5o) when the building was occupied between 8:00 to 17:00, irrespective of the orientation or time of day. As a result of that the electric lighting loads might not accurately corresponding to the measured data, hence, some degree of inaccuracy may arise.

Fixed louvers can be installed on the east and west elevations but will normally not protect occupants from the low sun in the early morning or late afternoon. In order to give more responsive shading, they should be motorised to allow louver angles to be adjusted. In this study, louvers were not adjustable due to the limitations associated with setting up the angle of the blades in a timely manner in the DesignBuilder simulation tool. As a result, fixed louvers will probably not be as effective as adjustable louvers to block low sun for the east and west orientations but it is expected to have a high energy-saving potential if using a higher coverage of louvers.

In this study, the effect of envelope measures on building energy consumption was assessed for a typical air-conditioned high-rise building. A mixed-mode (natural and mechanical) ventilation strategy, however, could effectively reduce the energy demand for cooling and mechanical ventilation. Using natural ventilation strategies might influence the selection of envelope measures to some degree. By placing the service areas along the external façade (as compared to the conventional central position), it might be possible to naturally ventilate the transitional spaces such as corridors in order to reduce the amount of energy that is needed for the operation of mechanical ventilation (or cooling). However, the possibility of applying natural ventilation in tropical conditions (low wind speed and high temperature) require a deep investigation on the fresh air requirements and the comfort temperatures for the naturally ventilated areas.

TOC

§ 4.9 Conclusion

For tropical climates, the effect of envelope measures on building energy consumption was assessed for an existing typical high-rise office building. Energy simulations as part of a sensitivity analysis defined 5 façade parameters with higher impact on building energy consumption; hence need more consideration for improvement. These measures were: shading type, glazing type, window-to-wall ratio, service core position and roof strategies.

A large number of computer simulations were run to evaluate the energy-saving potential of various design variables, as well as their combinations. The main findings of this study are outlined as follows:

- Choosing the right shading type has the highest effect on the buildings' energy efficiency in tropical climates. Using a combination of overhang and louvers with higher coverage on the east and west sides is the most effective strategy for solar heat control. Indoor blinds were found to be inefficient for controlling the solar heat gain. The application of indoor blinds can not only increase the electric lighting loads and reduce the view out but also contribute to overheating. The accumulation of heat between the slats and the glazing increases the indoor air temperature and consequently the cooling demand.
- Considering the glazing type, spectrally selective glazing (SHGC: 0.42 and light transmission coefficient: 0.68) resulted in the highest energy-savings. When using a high-performance shading system, the differences in energy saving between a single-, double-, and triple-glazed window reduced to less than 1%. In this condition, the more economical option might be selected over the most energy-efficient one. Glazing strategies that have a very low light transmission coefficient (e.g. reflective glazing) or use a DSF with a deep cavity (1.1 m) need more energy to supply artificial light; hence are not recommended for tropical climates.
- Assuming that windows are equally distributed across all building orientations without the provision of shading elements, energy-saving is the highest when the WWR is around 40% for all glazing types. This is the right balance for reducing heat transmission and increasing daylight access. By using external shading elements, the optimal WWR value raised to 80% (or more if possible). It is important to note that a high WWR should only be recommended for buildings with effective solar heat transmission control strategies like using a high-performance external shading system (such as S.10).
- The optimal position for the service core depends largely on the ability of the building envelope to reduce solar heat transmission through openings. In this regard, a westerly-oriented single-sided service core is the most energy-efficient option for a

poorly protected envelope (high solar heat transmission through the glazing) whereas a central service core is the most energy-efficient option for a well-protected envelope (low solar heat transmission through the glazing).

- The effect of roof design on the total energy performance of high-rise buildings is insignificant. The energy saving is limited to a maximum of 0.2% when adding roof top shading with an aluminium coating at 3.5 m distance from the roof.
- Finally, the integration of multiple high-performance design solutions offers a considerable saving in energy by around 36%, 34%, and 66% for total energy, cooling energy and electric lighting energy use, respectively. The combination of envelope measures is comprised of external shading (overhang and louvers), spectrally selective glazing, WWR of 80%, central service core, roof top shading with an aluminium coating, and air infiltration rate of 0.2 ac/h.

To summarise, a high-performance high-rise building in a tropical climate should have a well-protected envelope to control solar radiation, as the primary source of heat gain in tropical climates. In this regard, shading and glazing type are the two most important mediums through which the extent of the admittance of sun radiation can be controlled. Having a well-protected envelope, the WWR value can increase to 80% (or more) to increase daylight access for office areas that are located in the deeper parts of the floor plan. Furthermore, a glazing type with a high light transmission coefficient and adjustable louvers on the hot sides (east and west) can improve the daylight access to a higher level. According to the result of the sensitivity analysis, the effect of wall and roof insulation and of reflective materials for the external wall was found to be negligible in tropical climates. Therefore, these parameters were not part of the integrated design strategy. To achieve high levels of energy-saving, it is important to acquire a good understanding of how envelope measures can influence the total energy use (and different energy end-uses) individually and as a group. For example, a WWR of 80% or a central position for the service core would result in energy saving when combined with a high-performance shading and glazing system; while, for a poorly protected envelope (no shading and single pane glass) this configuration would not be optimal and would lead to a considerable increase in energy use.

TOC

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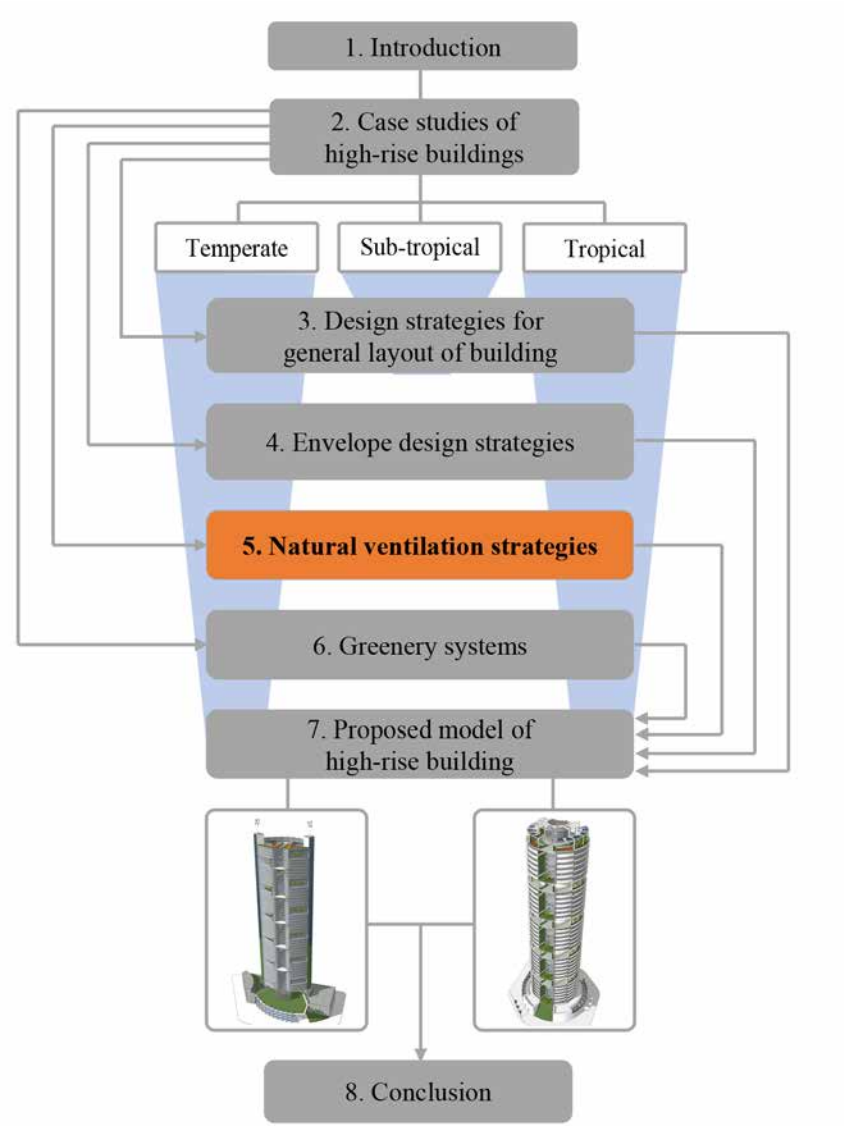
1. Introduction
2. Case studies of high-rise buildings
Temperate
Sub-tropical
Tropical
3. Design strategies for general layout of building
4. Envelope design strategies
5. Natural ventilation strategies
6. Greenery systems
7. Proposed model of high-rise building
8. Conclusion

5 Natural ventilation

In the previous chapters, the impact of geometric factors and envelope strategies for improving the energy performance of high-rise office building was investigated for various climates. The results of chapter 4 showed that the right combination of envelope strategies could reduce the total energy use by around 42% in temperate climates and around 36% in tropical climates. One other important difference between conventional and sustainable tall buildings is related to the application of natural ventilation. In chapter 5, the potential use of different natural ventilation strategies to reduce the energy demand for cooling and mechanical ventilation in high-rise buildings is investigated by using the same validated base models from chapter 4.

Chapter 5 starts with a thorough literature review on natural ventilation strategies that have been applied in multi-storey buildings. The rest of this chapter is presented in two parts (a and b) and will describe temperate and tropical climates respectively. The building- and climate-specific data such as the internal configuration of spaces and the frequency distribution of wind speed and wind direction are discussed separately for each part. Following that, a methodology section describes the methods for calculating fresh air amounts and comfort temperature along with the implemented airflow network model for CFD simulations. At the end of that section, the proposed natural ventilation strategies are precisely illustrated and defined. Results and discussions on the effectiveness of natural ventilation strategies for the temperate and tropical climates are provided in sections 5.5 and 5.9 respectively. A final section at the end of each part addresses the general conclusions of the findings.

§ 5.1 Introduction

The primary purpose of a ventilation system is to provide a healthy and comfortable indoor environment (Etheridge, 2010). The two main types of ventilation systems are natural and mechanical ventilation. Occasionally, natural ventilation (both supply and exhaust without mechanical means) may be perceived to be inadequate, especially with large commercial buildings and, therefore, a hybrid ventilation system is a way of reducing the risk (Etheridge, 2012). Hybrid ventilation solutions, also known as mixed-mode systems, use a combination of natural and mechanical ventilation in order to minimise energy consumption. Typically using natural ventilation when the

TOC

external conditions such as air temperature or wind speed are optimal, and switching the system to mechanical when the external conditions do not allow (Wood & Salib, 2013). There are some advantages and disadvantages when using a natural ventilation system. Perhaps the main advantage is by its contribution to a sustainable built environment. In commercial buildings, a substantial portion of energy is consumed by HVAC equipment, including fans. Recent studies show that fans account for roughly 15-20% of the total energy use in a multi-storey office building depending on climate and other factors (Raji et al., 2017; Rossi & Wolf, 2016). Purely natural ventilation systems idealistically require no energy for the supply of fresh air since the major forces for ventilation are wind and buoyancy. Mechanical means should only create under- or over-pressure in the limited occasions of lack of natural draft, creating a considerable reduction of energy use.

In addition to providing fresh air, natural ventilation plays a key role in maintaining thermal comfort and may lead to thermal energy-savings. When cooling is required for occupants' thermal comfort and the outdoor air temperature is lower than the indoor air temperature, outdoor fresh air can be used to achieve indoor cooling. This can be more beneficial in buildings with excessive internal or solar heat gains. Furthermore, ventilation has a direct cooling effect on the human body through convection and evaporation. In a naturally ventilated building, the ability of occupants to adapt to internal and external conditions is present, in the sense that having control over the indoor environment can extend the occupants' comfort range and reduces the need for active cooling (Nicol et al., 2012).

Despite benefits, natural ventilation systems have a number of drawbacks that are important to be aware of when designing naturally ventilated buildings. Natural ventilation can save space necessary for plant rooms and duct networks, but due to its strong dependence on weather conditions, occasionally, non-domestic buildings require vertical shafts such as atria or solar chimneys to improve the air flow rate, when wind speeds are low. In this case, minimising the efficient use of floor space in commercial buildings may be unfavourable from a commercial viewpoint (Wood & Salib, 2013). Furthermore, it is difficult to control natural ventilation and it only works for relatively narrow floor plans.

The driving forces for natural ventilation in high-rise buildings are similar to those for other building typologies. However, tall buildings can take advantage of the excessive height to enhance air velocity and therefore the occupants' comfort. Architectural features such as atria, solar chimneys and double-skin facades are increasingly incorporated into the design of high-rise buildings to assist natural ventilation (Wood & Salib, 2013). The interaction of heat and air flows between different building zones and these vertical shafts has been the topic of research until now (Holford & Hunt,

TOC

2003; Khanal & Lei, 2011; Khanal & Lei, 2012; Liping & Hien, 2007; Moosavi et al., 2014; Priyadarsini et al., 2004). The scope of this paper is to investigate the potential use of natural ventilation strategies to reduce the energy demand for cooling and mechanical ventilation for high-rise buildings in summer. The next section comprises a thorough literature review on natural ventilation strategies that have been applied in multi-storey buildings.

§ 5.2 An overview of previous studies

Comparing with conventional double-skin facades, Ding et al. (2005) investigated the potential performance of a solar chimney set on top of a double skin-façade building to enhance natural ventilation. According to the CFD results, a solar chimney with a minimum height of two floors on top of a double skin façade can increase pressure differences, hence the air change rate of intermediate floors. However, the number of air changes for the base and top floors varied significantly. For an even distribution of natural ventilation, Ding et al. suggested that the opening sizes of internal windows should not be the same at different floors.

Acred and Hunt (2014) used simplified mathematical models to define buoyancy-driven ventilation of an atrium in a multi-storey building. In agreement with the findings of the previous study, they found the minimum and maximum air flows for the floors located on the top and the ground level respectively. The reason is that at higher levels the required pressure which drives the air flow is less. They came up with a simplified method to help designers to choose the appropriate vent sizes needed on different storeys for a multi-storey building with an unheated atrium design.

Shafiei Fini and Moosavi (2016) investigated different atrium shapes with converging, diverging and vertical walls by using CFD simulations. The tilted walls have a 5° deviation from base to roof with a 8 m longest span. In all cases the atrium is located in the centre of a 10-storey building with an open plan layout (8 m depth) and the size of the air vents stayed the same for all floors. They found that an atrium design with converging walls enhanced the air velocity for base floors better than the others. No significant improvement in ventilation was observed for the case with diverging walls compared to the vertical one. The best performance, however, was achieved by an integrated atrium design that consisted of convergent walls for the base floors and vertical walls for the upper floors.

Prajongsan and Sharples (2012) investigated the potential performance of ventilation shafts in a single-sided residential unit during summer (February-May) in a tropical climate. Air velocities and the percentage of comfort hours in a hypothetical room with and without a ventilation shaft were assessed using EnergyPlus and the CFD code in the DesignBuilder software. The test room was located at the second-to-last floor of a 25-storey high-rise building and at the centre of the building floor. The room has access to natural ventilation from a centrally positioned window facing the prevailing wind direction, with 2.4 m^2 operable area, opened 24 hours a day. The proposed vertical shaft had a size of 0.6×2.0 m and it was placed at a distance of 6 m from the window. They found that the average air velocity in the room with a vertical shaft was substantially higher than in the room without a shaft under different wind conditions. Furthermore, they used Szokolay's physiological cooling equation to calculate the potential cooling effect of elevated air velocities from the application of the vertical shaft. Comparing the operative temperature inside the room with and without shaft, the result showed that the shaft was able to extend the comfort time from 37.5% to 56.3% during the summer.

Liu et al. (2009) assessed the efficiency of buoyancy-driven ventilation of an atrium building in a hot and humid climate using CFD combined with scale model tests. They found that the external ambient temperature has a larger impact on temperature variations in the atrium than the internal loads. When the atrium height is limited (4-storey) and the ambient air temperature is almost constant (such as in hot and humid climates), the buoyancy-driven ventilation is not very effective. In this case, a mixed-mode ventilation system might be necessary to provide the desired thermal comfort.

Stec (2006) investigated the potential benefits of employing double skin façade (DSF) in office buildings for improving the indoor comfort and reducing the energy consumption in the temperate climate of Netherlands. For the determination of the interaction between the DSF and indoor climate installations, three types of simulation models were employed. In order to investigate the impact of DSF on building energy consumption a simplified network model was used. Detailed pressure network model was employed for more accurate investigation of the airflow through the cavity. Finally, CFD modelling was used mainly for detailed analyses of the performance of the façade such as the position of the shading devices. All models were validated through a comparison with measured data and also in comparison with the generated results from VA114 building simulation program. The results showed that DSF has the ability to strongly improve indoor climate comfort and significantly reduce energy consumption without increasing the initial investment. Furthermore, it was found that the application of natural ventilation by the operable windows through a DSF in combination with simple algorithms for weather prediction would allow for significant energy consumption reductions that could even reach up to 70% when compared to a building with the single skin façade, internal blinds and conventional mechanical indoor climate system.

Through an overview of studies on natural ventilation systems, we found that buoyancy-driven ventilation by using atria or solar chimneys have been investigated for buildings with very limited height (low-rise buildings) for the majority of cases. The performance of the vertical shaft is highly influenced by the building height. As a result, for a better understanding of the performance of buoyancy-driven ventilation, more research is needed on tall buildings. Furthermore, a comparative study of different design strategies and their influences on natural ventilation for tall buildings could be very helpful from the architectural viewpoint since it can help architects to make energy-conscious decisions during the early-stage design.

PART A / TEMPERATE CLIMATE

Natural summer ventilation strategies for energy-saving in high-rise buildings: A case study in the Netherlands[4]

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Abstract

This paper investigates the potential use of natural ventilation strategies to reduce the energy demand for cooling and mechanical ventilation for high-rise buildings in summer. A 21-storey office building was selected to represent a mechanically ventilated high-rise design in temperate climates. Six natural ventilation scenarios were developed for the base design and the CFD package in DesignBuilder was used to predict their flow pattern under two summer conditions. Afterwards, the Operative temperature and the total fresh air changes per hour were calculated with EnergyPlus and were compared accordingly with European comfort standards. The percentage of discomfort hours indicates when a natural ventilation system would need active cooling or mechanical ventilation. Natural ventilation strategies can provide comfort conditions for up to 90% of the occupancy time in summer and therefore can save a significant amount of energy that is generally needed for the operation of traditional mechanical ventilation and air-conditioning systems.

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Keywords

Natural ventilation, energy efficiency, indoor comfort, high-rise office building, CFD.

§ 5.3 Temperate climate: EWI building

§ 5.3.1 Building design

The 21-storey case study building concerns the Faculty of Electrical Engineering, Mathematics and Computer Science (EWI) of the Delft University of Technology. The EWI building was completed in 1968, a time in which the building regulations had limited energy directives. The building has a rectangular plan with an aspect ratio of about 4.5:1. The building has multiple cores. Vertical circulation is provided by two staircases located at both ends of the corridor, and by a large core in the east of the building containing elevators and sanitary facilities. On each floor two plant rooms are located diagonally opposing each other. The building layout contains cellular offices along the west and east sides and a central corridor, as shown in Figure 5.1. The east- and west-facing facades consist of an outer single-glazed curtain wall and an inner single-glazed window enclosing a 95 cm cavity. The percentage of window-to-wall ratio (WWR) is higher for the external leaf (WWR: 95%) and lower for the internal leaf (WWR: 60%). While, the north- and south-facing facades (smaller sides) have no glazing. The inner windows cannot be opened since the building was designed to be mechanically ventilated. External vents allow the cavity to be naturally ventilated during summer. The cavity is continuous horizontally but segmented at each floor vertically. Fresh air enters the cavity through the air vents located in the middle of the facade, while the exhaust air is drawn out at both ends of the cavity. The ventilation system for the office rooms is different from that of the cavity. Ducts in the façade cavity bring in fresh air for the office rooms. The stale air passes through air grills at the bottom of the doors and is then extracted through exhaust units in the corridor.

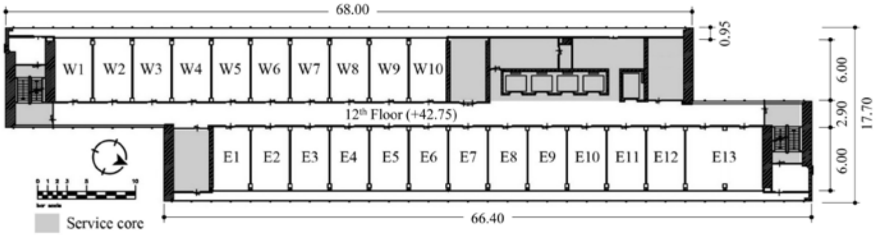


FIGURE 5.1 A typical floor plan of the EWI building and the location of studied rooms.

§ 5.3.2 Climate

The EWI building is located in Delft, a city in the Netherlands with a temperate maritime climate (Latitude 51° 59´N and Longitude 4° 22´E). The climate of this region is influenced by the North Sea and the Atlantic Ocean; this results in a relatively small annual temperature range, considerable precipitation and occasionally high wind speeds. This climate generally features cool summers and mild winters (see Figure 5.2). Winds are omnidirectional but the predominant wind is south-west and the annual average wind speed is around 4.3 m/s. In fall and winter strong Atlantic low-pressure systems can bring strong winds which cause uncomfortable weather. However, the wind speed is lower during summer (Figure 5.3). For this study, weather data were obtained from the nearby Royal Dutch Meteorological Institute (KNMI) weather station at Rotterdam-The Hague Airport (6.5 km south-east of the location). Since the energy consumption data measured were obtained in 2013, the weather data were also acquired from 2013.

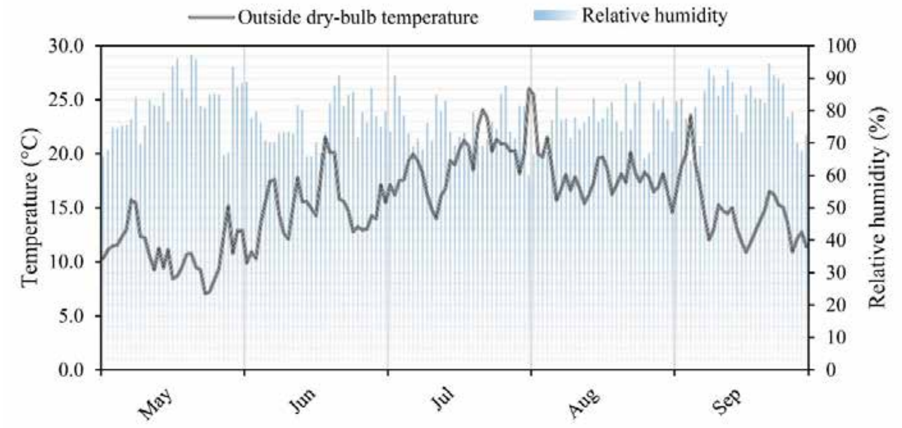


FIGURE 5.2 Mean daily values of dry-bulb temperature and relative humidity at Rotterdam Airport in summer 2013 (KNMI).

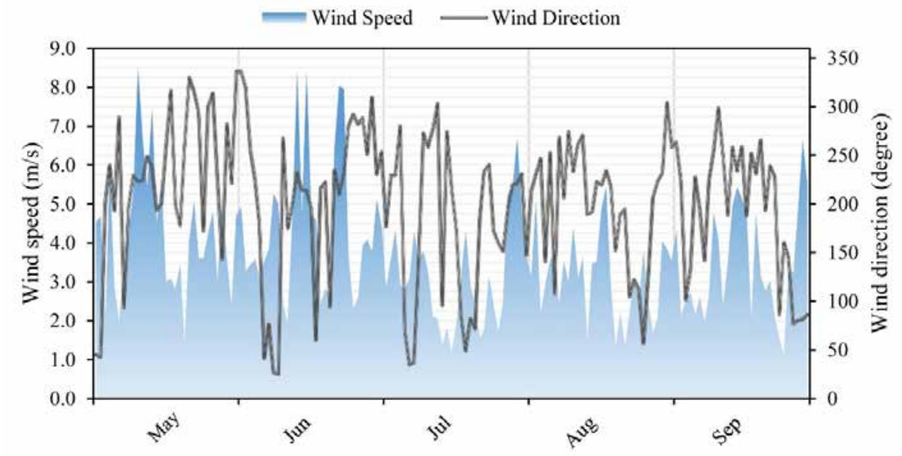


FIGURE 5.3 The daily wind speed and wind direction at Rotterdam Airport in summer 2013 (KNMI).

§ 5.4 Methodology

This study is a follow-up of Raji et al. (2016). In the first part, energy-saving measures such as glazing type, WWR and shading elements for the envelope design of high-rise office buildings in temperate climates were investigated with a special focus on cooling, heating and electric lighting. For this purpose, the EWI building was selected and the energy use prior to and after refurbishment was compared through computer simulations with DesignBuilder. The simulation model in DesignBuilder was validated using detailed metered energy data.

The follow-up study presented here aims at addressing the potential use of natural ventilation as a replacement strategy for mechanical ventilation systems by extending our investigation using the same validated base model from Raji et al. (2016). For this purpose, six natural ventilation strategies were developed for the base case by changing the design parameters including the façade type (single layer façade versus double skin façade), the size of air inlets/outlets (the percentage of operable window area), and the application of vertical shafts (e.g. atrium and solar chimney). Through the application of different ventilation strategies, this research aims at addressing the following questions:

- What is the percentage of the occupancy time in summer that natural ventilation can provide sufficient fresh air in the office rooms?
- What is the percentage of the occupancy time in summer that natural ventilation can provide enough cooling to keep the indoor temperature in the office rooms within the comfort range?
- Among the considered alternatives, which of the natural ventilation strategies can save the most energy?

In this study, the investigation of natural ventilation (NV) strategies comprises of two main steps, as shown in Figure 5.4. The objective of the first step is to predict the impact of different ventilation strategies on air flow patterns and temperature distribution in one office floor under two different weather conditions: a typical summer condition versus an extreme summer condition. In the second step, the energy-saving potential of the six NV strategies for ventilation and cooling will be analysed for all rooms facing east and west at a middle high floor (12th storey) in summer (May-Sep).

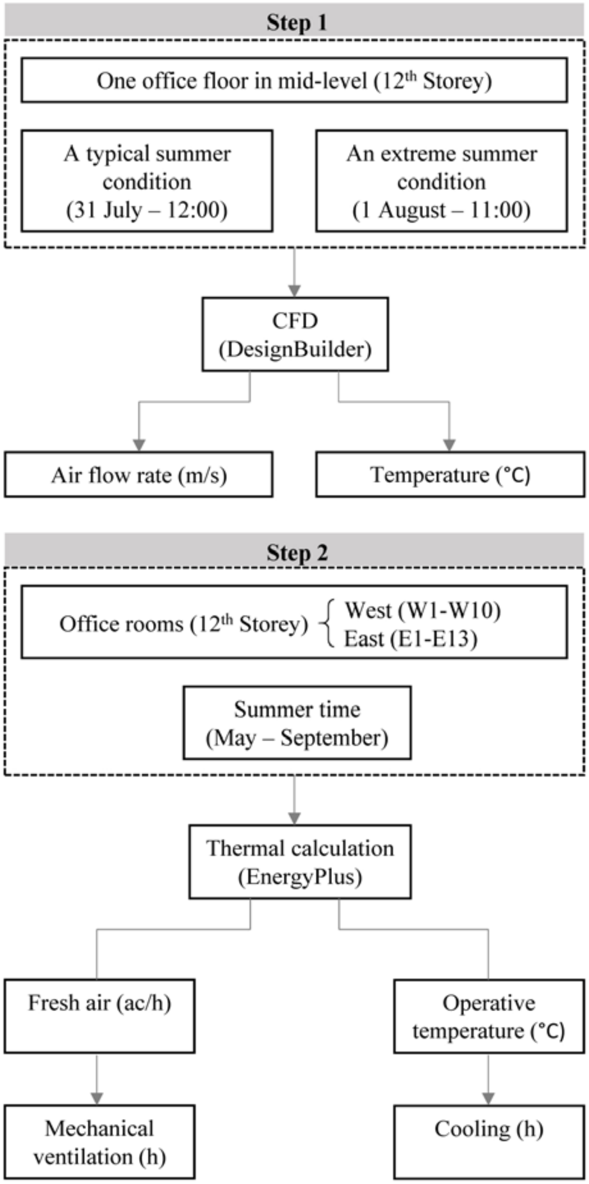


FIGURE 5.4 Methodological scheme of research.

§ 5.4.1 Fresh air calculation

There are two approaches for modelling natural ventilation in DesignBuilder, i.e. scheduled and calculated. In this study, the natural ventilation model option is set to "calculated". The calculated option allows for the calculation of natural ventilation based on opening and crack sizes, buoyancy and wind pressures. This will increase the complexity of the model and simulation run time, but it is the preferred option when designing a natural ventilation strategy. The EnergyPlus multi-zone airflow network model allows to identify multiple flow paths through the building, i.e. internal flows between spaces are taken into account. When the calculated natural ventilation option is selected, the EnergyPlus air flow network use wind pressure coefficients on each surface during the simulations. The solar radiation distribution is set to "full interior and exterior". This option calculates the amount of beam radiation on each surface within the zone through the exterior windows, while also taking into account the effect of window shading devices.

For the operation of natural ventilation, a control mode was defined based on zone temperature. All the external openings can be opened if $T_{in}>T_{out}$ and $T_{in}>T_{set}$ and the operation schedule (occupancy hours 7:00 – 19:00) allows ventilation to occur. Here, T_{set} is the zone-based air temperature setpoint for the operation of external windows. In this study, 22 °C was selected for the T_{set} during the summer because the number of discomfort hours in office zone (and therefore the energy use) was increased slightly when selecting values higher or lower than 22 °C. When the zone temperature is lower than T_{set}, the external windows will be automatically closed to avoid unnecessary heat loss and draft during the cooler periods of the day (mostly early morning hours) in summer. In such conditions, the ventilation system might switch to mechanical ventilation to provide fresh air. For the proposed natural ventilation scenarios with a DSF, the internal windows are controlled entirely by schedule and are not affected by temperature controls. The building- and occupancy-related parameters with selected values used for the simulations are summarised in Table 5.1.

TOC

PARAMETER	VALUES	
External wall insulation	2.22 W/m^2-K	
Roof insulation	1.91 W/m^2-K	
Glazing type A [1]	DSF: inner pane: [Sgl: Clr 10 mm]; outer pane: [Sgl: Tinted 10 mm]	
U-value	1.48 W/m^2-K	
Light transmission	0.22	
Glazing type B [2]	DSF: inner pane: [Dbl: Clr 6 mm/6 mm air/6 mm]; outer pane: [Sgl: Clr 10 mm]	
U-value	1.09 W/m^2-K	
Light transmission	0.44	
Glazing type C [3]	[Dbl LoE (e2=.1) Clr 6mm/13mm Arg]	
U-value	1.49 W/m^2-K	
Light transmission	0.74	
Shading	Blinds (inside) with high-reflectivity slats	
Shading operation schedule	Weekdays: 7:00–19:00; weekends: no operation	
Metabolic rate	0.9 met (average value for men and women)	
Occupancy density	4 person/room (0.16 people/m^2)	
Occupancy schedule	7:00 – 19:00 h (Mon-Fri)	
External vents operation	Always on	
Minimum T_{set} for natural ventilation (air temperature)	Office zone	22 °C
	Atrium zone	18 °C
	Cavity zone	10 °C

1 Glazing type A is selected for reference design.
2 Glazing type B is selected for NV#1 and NV#2.
3 Glazing type C is selected for NV#3, NV#4, NV#5, and NV#6.

TABLE 5.1 Building and occupancy parameters and the proposed values for the simulation.

According to the Dutch building code (Bouwbesluit, 2011), the fresh air minimally required for light office work is around 6.5 l/s per person. Since all of the office rooms are identical and the occupancy rate is available, the minimum requirement concerning air changes per hour can be calculated with the following equation:

Quantity of fresh air (l/s) = Air change rate (changes per h) x Room volume (m^3) x 1000/3600

For the purpose of fresh air calculation, office rooms are assumed to be fully occupied (four persons /office room). Therefore, a total amount of 26 l/s of fresh air is needed to ventilate 110 m^3 of the space. This means that each office requires a minimum of 0.85 ac/h to provide enough fresh air for the occupants. The total amount of fresh air changes per hour in all office rooms was simulated in EnergyPlus for the different ventilation strategies. The percentage of hours in which the ac/h was less than the

TOC

minimum required value was obtained for all office rooms. In case of the meeting room (E13), it is supposed that the room volume and the occupancy rate increase by two and four respectively, as a result the minimum required fresh air would be higher compared to other office rooms.

§ 5.4.2 Computational Fluid Dynamics (CFD)

The air flow rate and the temperature distribution in the building were simulated with the help of Computational Fluid Dynamics (CFD). In this study, the CFD code from DesignBuilder version 3.4 was employed. The most widely used and tested turbulence model, k-ε turbulence model, was selected among others that is belonged to the RANS family of models (Cheung & Liu, 2011; Nielsen, 1998; Ramponi & Blocken, 2012). The DesignBuilder's CFD code has been validated by a number of studies through a comparison with measured data from existing buildings (Baharvand et al., 2013; Chung et al., 2014) and also in comparison with the generated results from other CFD packages (Northumbria University, 2011). Using the CFD package in DesignBuilder simplifies the input of boundary conditions, since there is the possibility of using previously calculated quantities of temperatures, heat flows and flow rates from EnergyPlus. In this study, the number of outer iterations was initially set at 3000. This means that the calculations will terminate when the number of iterations reaches this value. In some cases when the solution has not converged, the number of iterations was gradually increased and the variation of the dependent variables was carefully monitored throughout the calculation in order to observe the point at which they finally stabilise. The CFD simulation results were taken as valid solution only when residual Root Mean Square Error (RMSE) values have reduced to 1E-5 and the selected dependent variable for the currently selected monitor cell reached a steady final value.

Grid size is an important factor in CFD simulations because the accuracy of the results depends highly on the grid definition (Gebreslassie et al., 2012). The grid used by DesignBuilder is a non-uniform 3D Cartesian grid. It means that the grid lines are parallel with the main axes, and the grid regions (the distance between grid lines) enable non-uniformity. In this study, a grid sensitivity test was carried out. A diverse range of grid samples from extremely coarse (0.5 m) to very fine (0.1 m) were modelled for the computational domain (one floor at the mid-level) and air velocities were carefully monitored for different ventilation scenarios during a typical summer condition (31 July, 12:00). For the proposed model geometry, a grid structure couldn't be generated with very fine grid size (0.1 m) because it requires a large amount of memory, especially when the model domain is remarkably large. The simulation results obtained for fine (0.2 m) and medium (0.3 m) grid samples were almost identical and the relative error of maximum air velocity was found to be less than 1%. However, the relative error increased to 3% and 8% for coarse (0.4 m) and very coarse (0.5 m) grid sizes respectively. According to the results, the medium grid size (0.3 m) is a good compromise between the fine and coarse grid sizes since it can satisfy the accuracy of solutions, while also avoid long calculation times. Therefore, in this study a grid spacing of 0.3 m with 0.03 m default grid line merge tolerance was defined for the computational domain. A 3D CFD grid was generated based on the key points from the model geometry along each of the major axes and the grid spacing and the grid line merge tolerance entered on the calculation option dialog. As a result, a 3D structure of grids consists a total number of 403848 cells (316×71×18) was made for the CFD experiments.

There is no dominant barrier in the proximity of the EWI building to block or reduce wind flows at the mid-height around this building. Therefore, the effect of wind flow is considered to be at its highest level (wind factor: 1). A default discharge coefficient of 0.65 is used for windows, doors and holes. DesignBuilder is supplied with a databases of wind pressure coefficients (C_p) from Liddament (1986) which suits best for buildings of 3-storeys or less. However, for tall buildings (when height is more than three times the crosswind width), it is recommended to override this default data. Ideally, the specific pressure coefficient data should be obtained from wind tunnel measurements using scale models of the building (ASHRAE, 2005). However, wind tunnel testing is a very expensive and time-consuming method and therefore might not be applicable if the object that is being tested is too big. The wind pressure coefficients used in the present study were obtained from the experimental work of Davenport and Hui (1982). They determined the local pressure coefficients of a tall rectangular high-rise building located in urban terrain. The data are given in 15° increments and for different points on the façade.

The CFD simulations were carried out for two distinct scenarios: a typical summer condition and an extreme summer condition (see Table 5.2). The former (31 July, 12:00) represents a typical summer day with an outdoor air temperature of 22 °C and wind speed (4.5 m/s) coming from the prevalent direction (south-west). The performance of the NV strategies was also tested for an extreme weather condition (1 August, 11:00): a high temperature (29 °C) and a low wind speed (1.5 m/s). According to Figure 5.5, a wind speed of 4-5 m/s from the south-west is most frequent during summer while for the minimum average wind speed (1-2 m/s), the north-east is the dominant direction.

TOC

	Outdoor dry-bulb temperature (°C)	Wind speed (m/s)	Wind direction (degree)
31 July	22	4.5	225° (SW)
1 August	29	1.5	45° (NE)

TABLE 5.2 The proposed weather scenarios for CFD simulations.

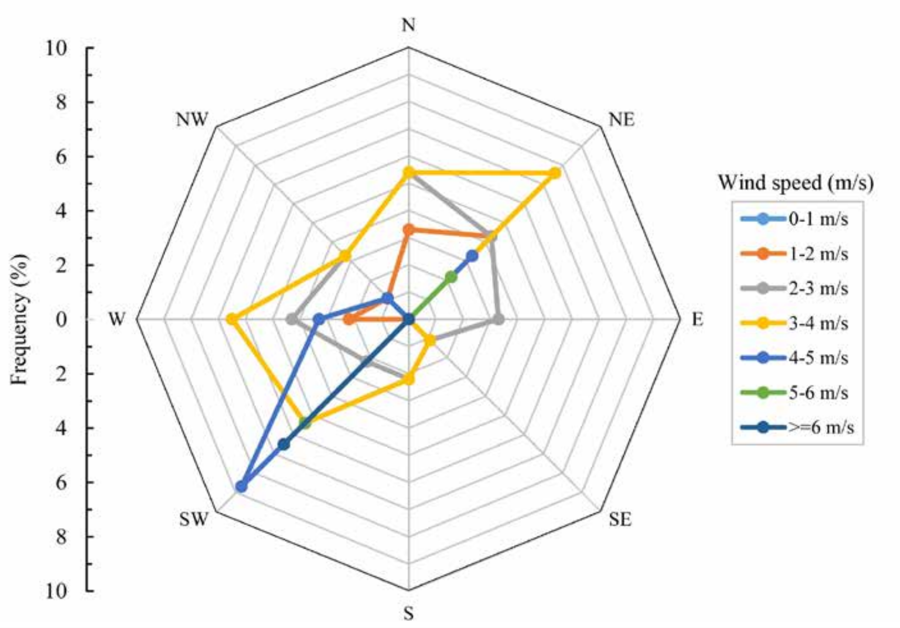


FIGURE 5.5 Frequency distribution of wind speed and direction at Rotterdam Airport in the year 2013 (May-Sep).

§ 5.4.3 Comfort temperature calculation

The impact of ventilation strategies on the occupants' thermal comfort during the summer (May-September) was assessed using the adaptive equations for comfort in free running buildings from the European standard (EN15251, 2007). In 2007, the European Committee for Standardisation (CEN) released the following equation for naturally ventilated buildings:

$T_{comf} = 0.33 \times T_{rm7} + 18.8\ °C$

Where T_{rm7} is the exponentially weighted mean outdoor temperature for the last 7 days and is calculated with the following approximation:

$T_{rm7} = (T_{-1} + 0.8\ T_{-2} + 0.6\ T_{-3} + 0.5\ T_{-4} + 0.4\ T_{-5} + 0.3\ T_{-6} + 0.2\ T_{-7})\ /\ 3.8$

A comfort temperature range was selected with 80% acceptability limits, which represents the category of normal expectancy for new buildings and renovations. These 80% acceptability limits introduce a boundary around the comfort temperature of ±3 °C.

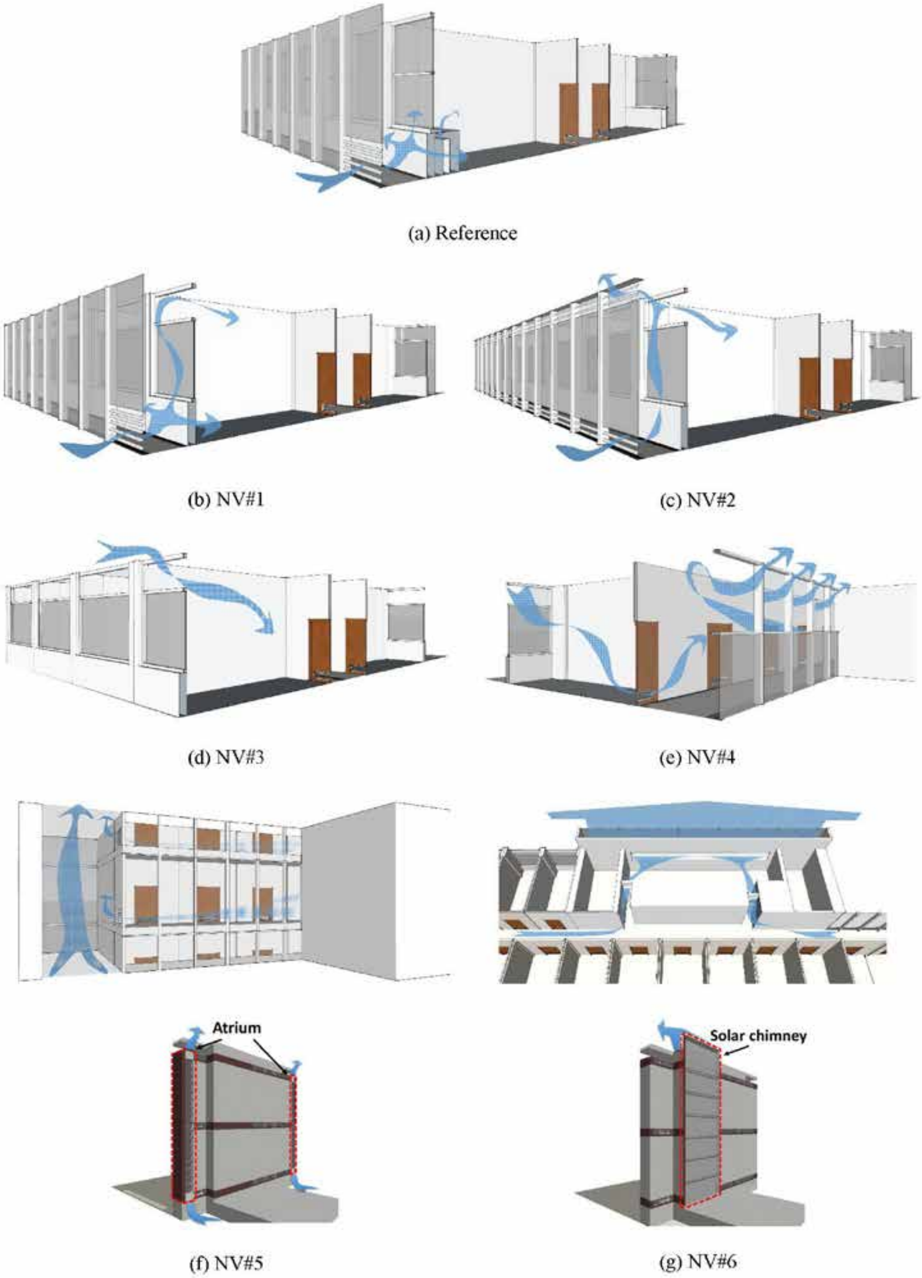
§ 5.4.4 Proposed natural ventilation strategies

Natural ventilation design can be separated into two aspects, the entry and exit of air through the envelope and the air movement within the internal spaces. The former phenomenon is influenced by the characteristic of the openings (air inlets and outlets) in the envelope design, whereas the latter is affected by the plan configuration, interior walls, grills and doors (resistance of the flow path) of the occupied space.

In this study six different ventilation scenarios were developed for the base case using single-sided, cross or stack ventilation or a combination of them. Detailed information for the six proposed ventilation strategies in line with their visual representations are provided in Table 5.3 and Figure 5.6, respectively. This study investigates the potential use of natural ventilation strategies to reduce the energy demand for cooling and mechanical ventilation for high-rise buildings during the summer in the temperate climates. The reference building has a double-skin facade (DSF) with one external vent per 28 meters (three vents each side; two at corners 2.00 × 3.75, and one in middle 4.00 × 0.90) for natural ventilation inside the cavity, but there is no internal operable window and therefore the building fully relies on fans and air-conditioning for providing comfort conditions (Figure 5.6a). For the reference design, small air grills (1.00 × 0.15) are embedded at the bottom of the doors so that the stale air can be extracted to the corridor. These air grills were kept unchanged in all ventilation strategies to have a better air circulation through the internal spaces.

REFERENCE	DSF with fixed windows (fully air-conditioned)
NV#1	DSF with external vents as designed in reference building and 30% operable internal windows
NV#2	DSF with external vents improved in size and 30% operable internal windows
NV#3	Single skin façade with 30% operable external windows (except the openings in the corridor)
NV#4	NV#3 combined with 50% operable windows in the corridor
NV#5	NV#3 combined with two atria at the both ends of the corridor
NV#6	NV#3 combined with a solar chimney

TABLE 5.3 Proposed natural ventilation strategies versus the reference design.



(a) Reference

(b) NV#1

(c) NV#2

(d) NV#3

(e) NV#4

(f) NV#5

(g) NV#6

FIGURE 5.6 Proposed ventilation strategies and the reference design. Arrows show the intended flow pattern within the ventilated spaces.

Among the six proposed ventilation strategies, two of them have a DSF and the other four have a single skin façade. For the first ventilation strategy (NV#1) fixed internal windows are changed to 30% operable while the external leaf has the same features as the reference building. The operable windows have a size of 3.6 × 2.7 m (W × L) and are located 1 m above the floor in the centre of the external wall. The position of the aperture of all operable windows (internal and external) is located on top and the aperture size is 30% of the total window area. The air flow opening is assumed to be a gap in the window. It means that 3 m^2 of each window area can be opened for the purpose of ventilation through the top of the window. For NV#2 the size and number of external vents is increased by reducing the glazing area and adding horizontal air inlets (bottom) and outlets (top) along the entire east and west façade with a height of 45 cm (Figure 5.6c).

In order to change the façade type to a single skin, the internal leaf is moved 95 cm towards the outside so that the external layer is replaced without changing the window size (Figure 5.6d). Only the glazing type changed to improve the energy performance. As a result, the new single skin façade is characterised by a double-glazed low-e clear glass pane with a U-value of 1.49 (W/m^2 K) and 58% solar transmittance (g-value). The main difference between NV#4 and NV#3 is the operation of external windows located in the corridor. For all ventilation scenarios, external windows in the corridor (located at both ends) are not operable except NV#4 that takes advantage of 50% operable windows in the corridor (Figure 5.6e).

For the last two natural ventilation scenarios, the potential of stack ventilation through the application of vertical shafts such as an atrium or a solar chimney is tested. In NV#5 two atria are added at the both ends of the corridor. Each atrium has a dimension of 4.7×9.6 m and it is extended vertically along the building height without any segmentation. The atria have access to external walls from three sides and the fourth side has connections with the corridor by an air vent at floor levels. The east and west walls are fully glazed but they are not operable. The air inlets and outlets are located on the lowest and highest floor of the building (Figure 5.6f).

The solar chimney (NV#6) employs a vertical shaft (1.4×24.6×83.2 m) with an exhaust vent at its top and is attached to the western external wall behind the service area. The shaft extends 6 m above roof level and the exhaust vents are facing towards east (against the predominant wind direction). The dimension of the air outlet is 5.0×24.2 m. In order to increase the thermal buoyancy within the solar chimney, the external leaf was fully-glazed with a single skin 6 mm clear glass pane and the interior leaf painted black (by using a dark surface layer) to absorb more radiation (Figure 5.6g).

The air paths between rooms and corridor is expected to be highly dependent on the type of natural ventilation strategy. For the reference design, the stale air passes through air grills at the bottom of the doors and is then extracted mechanically through exhaust units in the corridor. In NV#1, NV#2 and NV#3, a single-sided ventilation is expected. This means that the stale air is extracted through the opening on the same side it enters. In NV#4, NV#5 and NV#6, ventilation elements that are placed along the corridor of the building are expected to improve the flow rates and assist in drawing fresh air into and through the offices. The stale air passes through air grills at the bottom of the doors and is then extracted naturally through 50% operable windows in the corridor (located at both ends) or pulled up into a vertical shaft (atrium or solar chimney).

§ 5.5 Results and discussion

§ 5.5.1 Air flow patterns

Figures 5.7 and 5.8 show the air velocity contours and average air flow rate for different natural ventilation scenarios under two environmental conditions; a typical summer condition (31 July) and an extreme summer condition (1 August). The horizontal section of air velocity was taken approximately 1.2 m above the floor which could be seen as representative for the sitting position of office workers. Since the focus of this study is mainly on office rooms, the results of the CFD simulations for the service areas (staircases, plant rooms and sanitary spaces) were faded to avoid confusion. However, when they are used as part of the ventilation strategy as in the case of the atrium (NV#5) or the solar chimney (NV#6), the CFD results also cover those areas. Apart from the horizontal section, a vertical section of air velocity across the rooms W7 and E3 was taken to provide further information regarding the average wind speed and the air flow path across west-east rooms. The vertical section passes through the centre of the rooms as presented in Appendix 1.

Generally, in a typical summer condition, the average air velocity was higher for ventilation strategies that were applied to a single skin facade in comparison to a DSF. Although the building features a cellular plan layout, cross-ventilation for the rooms facing each other can occur through the air grills in the doors. This cross-ventilation is

TOC

more likely to occur for higher wind speeds and for ventilation scenarios with a greater pressure difference between the rooms facing each other.

As can be seen in NV#1, the air velocity reduces considerably prior to entering the room. However, pressure differences between east and west rooms induce an air flow at floor level through the air grills in the doors.

In NV#2, increasing the size of air inlets and outlets for the external leaf lead to a reduction of areas of low wind speed for west-side rooms but its effect on east-side rooms was negligible.

Changing the façade type to a single skin (NV#3) lets the wind enter the rooms deeper from the windward side but again the influence on east rooms was not considerable due to the partition walls.

In NV#4, cross-ventilation inside the corridor was developed by changing the external windows of the corridor to 50% operable. The CFD results show that the cross-ventilation flow through the long corridor increases the average air velocity not only in corridor (up to 0.3 m/s) but also in the east-side rooms.

The influence of an atrium (NV#5) on air distribution and velocity was tested using the staircases at both ends of the corridor. The atria are designed here as a way to exhaust the stale air from offices to outside. This means the upward air flow in the atria is supposed to suck out the air from rooms into the corridor and from there, with the help of two air vents at the both ends of corridor, into the vertical shaft of atria. In practice, the two atria were not able to improve the air speed inside the corridor and rooms compared to the ventilation scenario without atrium (NV#3). Due to structural and architectural plan restrictions at the EWI building, the two atria have limited solar gain as windows are only in two directions (north and south). The solar heat gain in the atria, therefore, was not big enough to generate significant temperature variations between the ground floor and the top floor. As a result, the vertical shafts were not being able to induce the buoyancy driven ventilation and the atria space had a very low performance.

A solar chimney structure was proposed as strategy NV#6 in order to test its potential for natural ventilation. The stale air is drawn from the corridor into the service core and then through a large vent sucked out to the solar chimney. The air inlet for the chimney is 1.2 meters wide and 15.0 meters long and it is located 2.0 meter above the floor level in the service core. The CFD results show that under typical summer conditions the solar chimney performs as an air extraction system and can increase the air velocity inside the corridor and east room better than other ventilation strategies, except NV#4.

TOC

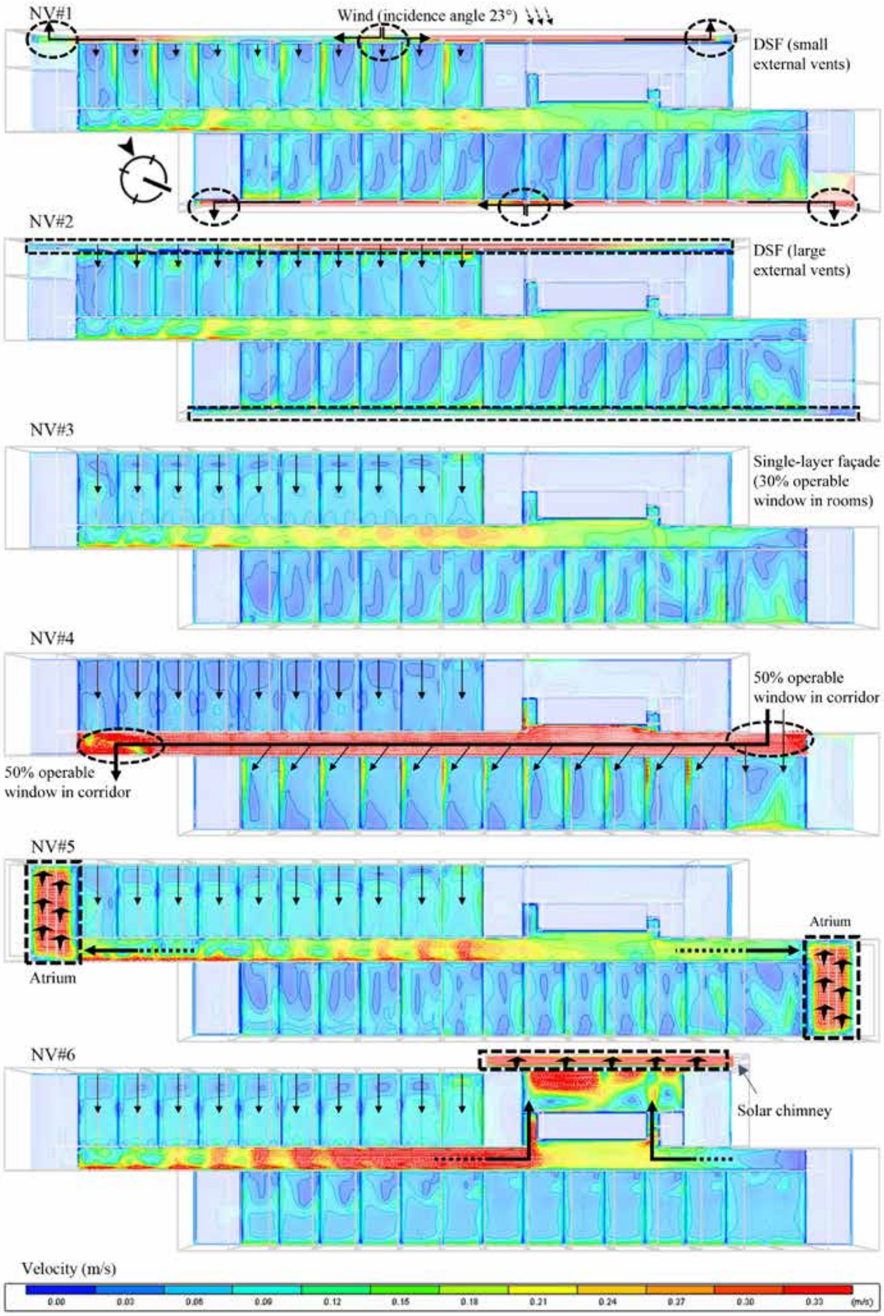


FIGURE 5.7 The magnitude and direction of air flow through the plan for six ventilation strategies under wind speed of 4.5 m/s and outside air temperature of 22 °C (31 July, 12:00 pm).

TOC

In case of extreme summer conditions (see Figure 5.8), the average air velocity for east-facing rooms were similar among ventilation strategies at a range of 0.03 m/s. For west-side rooms the highest air velocity was achieved by the application of a solar chimney. However, the CFD results for the extreme conditions show that a reverse flow exists in the chimney. The occurrence of the reverse flow results in a reduction of the air flow rate through the solar chimney and heat penetration into the building which is not desirable for ventilation (Khanal & Lei, 2012). Due to the high outdoor air temperature and excessive internal gains, the indoor air temperature near the inlet was higher than the backflow air temperature at the exit of the solar chimney system, and therefore the air goes downward in the chimney. Using operable windows inside the corridor (NV#4) can lead to a considerable increase of air velocity by up to 0.33 m/s within the corridor, even in low wind speed conditions (1.5 m/s). Among the 6 proposed ventilation strategies, the lowest air velocity was achieved by the application of atrium (NV#5), 0.03 m/s in western and eastern side rooms. Two openings (3.7 × 3.5 m) in the base and top of the atrium provides air flow (direct ventilation) into and along the atrium height (63 m). Direct ventilation of the atrium causes small temperature differences between internal and external spaces, so that bouncy-induced natural ventilation to be reduced. On the other hand, direct ventilation of the atrium interrupts the smooth flow of air through the connecting air grills between the corridor and the two atria.

TOC

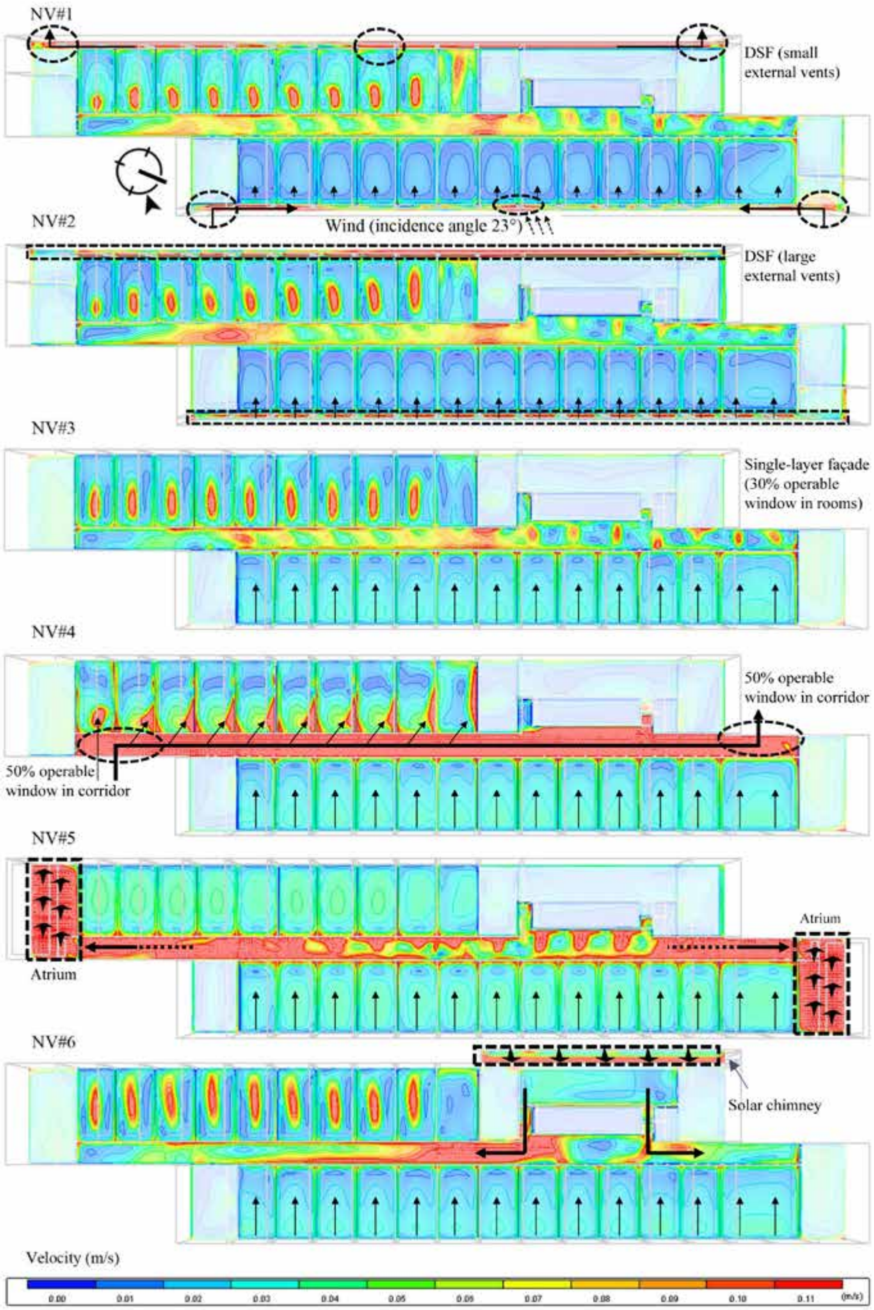


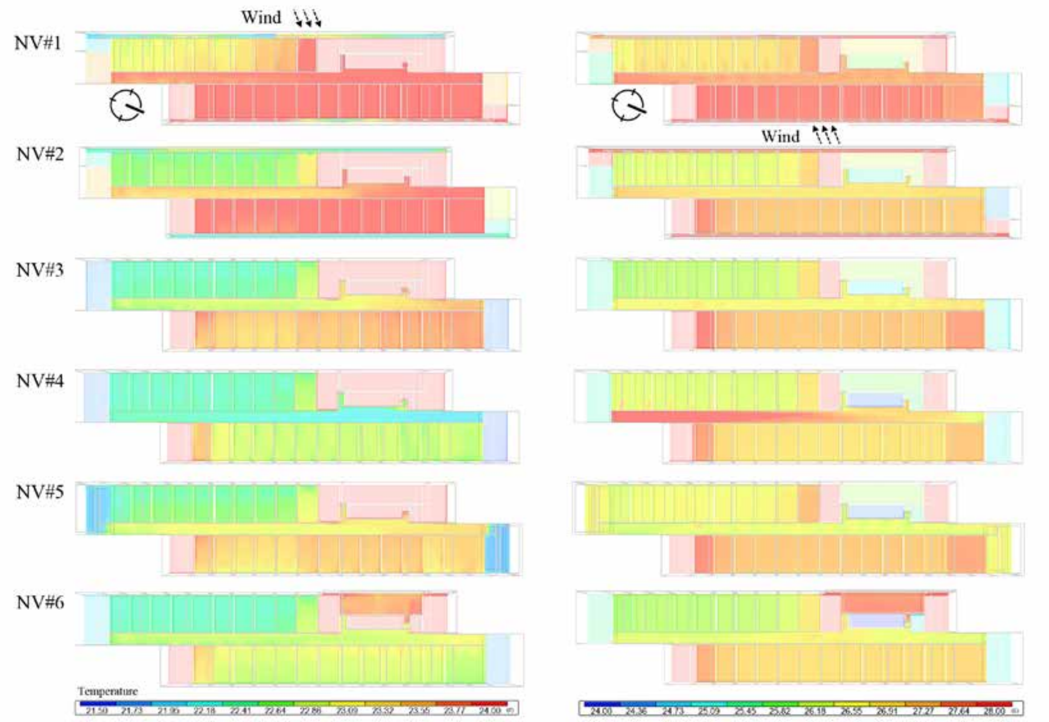
FIGURE 5.8 The magnitude and direction of air flow through the plan for six ventilation strategies under wind speed of 1.5 m/s and outside air temperature of 29 °C (1 August, 11:00 am).

§ 5.5.2 Indoor air temperature

The air temperature distribution for the six natural ventilation strategies is presented in Figure 5.9. In naturally ventilated buildings, the occupants' perception of indoor thermal comfort depends largely on the outdoor air temperature variations. So if the indoor air temperature is within the comfort boundaries set by the adaptive thermal comfort model (Nicol et al., 2012), the ventilation strategy can be considered successful. Generally, the results show that the cellular offices that are located in the corners have higher indoor air temperatures compared to those located in the centre of the plan. That is the result of heat transmission from adjacent spaces that are not ventilated, such as plant rooms.

Since the CFD simulations were carried out for two snapshots around noon, it is expected that the east-facing offices have higher air temperatures than the west-facing offices because the first have received more solar radiation during the morning hours. The results also generally show a higher indoor air temperature for the natural ventilation strategies that were combined with a double skin façade (NV# 1 & NV#2). The internal configuration of the cavity in a DSF can influence the resistance of the air flow path, hence might increase the risk of overheating in summer if not ventilated adequately. Therefore, the design requires more consideration compared to conventional single skin façades. Increasing the vent size in NV#2, results in a reduction of the indoor air temperature by about 0.5 °C, with higher impact for rooms directly facing the wind.

For a typical summer condition when the outdoor air temperature is 22 °C and the dominant wind direction is south-west, three ventilation scenarios lead to a lower temperature for west-side rooms, i.e. NV#3, NV#4 and NV#6. In NV#4 due to higher ventilation rates, lower air temperatures are achieved inside the corridor and the east-facing rooms (see Figure 5.9a). In a typical summer condition, the application of atrium (NV#5) resulted in slightly higher air temperature in the corridor and west-facing office rooms compared to NV#3 (single-sided ventilation). Therefore; there is no noticeable enhancement of air flows with the application of two peripheral atria in this case.



(a) Typical summer condition

(b) Extreme summer condition

FIGURE 5.9 The air temperature on one floor for six ventilation strategies under two weather conditions; (a) wind speed of 4.5 m/s and outside air temperature of 22 °C (31 July, 12:00 pm), and (b) wind speed of 1.5 m/s and outside air temperature of 29 °C (1 August, 11:00 am).

§ 5.5.3 Indoor comfort

Thermal comfort and fresh air are among the main indoor comfort indicators. Using natural driving forces, comfort conditions can be improved to a different extent depending on the design and local weather conditions. Six ventilation strategies were simulated for different office rooms in the EnergyPlus calculation core of DesignBuilder. The amount of discomfort hours during the occupancy time in summer determines the number of hours that active cooling or mechanical ventilation is necessary to provide comfort conditions in the office rooms. A lower number of discomfort hours means that the ventilation strategy performs better; hence save more energy.

§ 5.5.3.1 Fresh air changes

The percentage of hours in which the ac/h was less than the minimum required value (0.85) was obtained for all office rooms, as shown in Figure 5.10. This graph shows the percentage of time during office hours (7:00 – 19:00) in which natural ventilation alone cannot meet the minimum requirement for fresh air and, therefore, supplementary mechanical ventilation is needed. This has two reasons. Either, the natural ventilation control mode does not allow the window to be opened (e.g. if $T_{out} > T_{in}$ or $T_{in} < T_{set}$) or the window is open but the required fresh air cannot be generated due to undesirable wind direction (perpendicular to building sides with no opening) and/or too low wind speed.

The simulation results for ventilation strategies are quite promising. For all natural ventilation strategies, the need for mechanical ventilation reduced to less than 8% of the occupancy hours in western and eastern side rooms, except for two rooms that are located in the corners (W1 & E13). The lowest demand for mechanical ventilation achieved by natural ventilation strategy with a double skin façade and larger external vents (NV#2). The use of DSF regulates pressure distribution across the envelope and helps the air flow to be distributed more evenly on different rooms. Additionally, a DSF acts as a thermal buffer. Solar gain in the double-skin cavity can serve to preheat fresh air before it enters the rooms during the cooler periods of the day (mostly early morning hours) in summer. As a result, office rooms can benefit from natural ventilation for a longer period. However, careful consideration should be given to the design of a DSF. If the cavity is not sufficiently ventilated or shaded, the rooms can experience discomfort conditions (e.g. overheating).

As shown in Figure 5.10, the average percentage of discomfort hours (when mechanical ventilation is necessary) is almost equal for eastern and western side rooms among all ventilations strategies, except for NV#1. In NV#1, the configuration of the external vents is the same as the reference design. The fresh air is brought in from the centre of the façade and sucked out at the ends of the cavity's corridor. The result shows that west-facing rooms need more mechanical ventilation compared to east-facing rooms in order to provide the minimum fresh air requirements in office rooms in summer. This means that the design of external vents (position and sizing) in NV#1 is not as effective as NV#2 in providing proper pressure distribution within the natural ventilation system.

The ventilation strategy with an atrium (NV#5) shows the highest demand for mechanical ventilation. The first reason is related to the efficiency of the proposed atria in extreme summer conditions which has the lowest air velocity in east- and west-facing rooms (as can be seen in Appendix 1) and therefore the minimum average

TOC

number of air changes per hour among the six ventilation scenarios. Additionally, in order to provide natural ventilation for a longer period inside the building and to reduce the cooling demand, the minimum indoor temperature (T_{set}) for ventilation was set at 18 °C for the atrium which will allow the fresh air to circulate when the indoor temperature inside the atrium is equal to or above 18 °C. As a result, the temperature within the corridor reduces while the minimum ventilation set-point temperature in rooms is defined at 22 °C similar to other ventilation strategies. In case of a reverse flow in the atria, it is more probable for the temperature inside the office rooms to drop below the T_{set} and therefore, the windows inside the office rooms to be closed by control systems to avoid uncomfortable conditions.

All of the ventilation scenarios with a single skin façade (NV# 3 – 6) show slightly higher demand for mechanical ventilation. Generally, the use of a single skin façade, as opposed to a double skin façade, allows fresh air to enter the building with minimal obstructions, so that the internal air temperature might drop below the T_{set} more often due to a higher number of air changes per hour. To avoid uncomfortable conditions, the BMS automatically closes ventilation openings on the external façade and activates mechanical ventilation system.

The results show that the percentage of discomfort hours might vary according to the location of rooms. It is higher for the rooms located in the corners compared to rooms with a more central positioning. These differences are more distinguishable for natural ventilation strategies that are being provided through a single skin façade. Among them, natural ventilation solutions using a solar chimney (NV#6) or 30% external operable windows (NV#3) were providing the required fresh air for the longest period, respectively for the west and east offices in summer. Adding operable windows in the corridor (NV#4) to NV#3 has no significant influence on the east rooms but increases the percentage of time that the west rooms need mechanical ventilation.

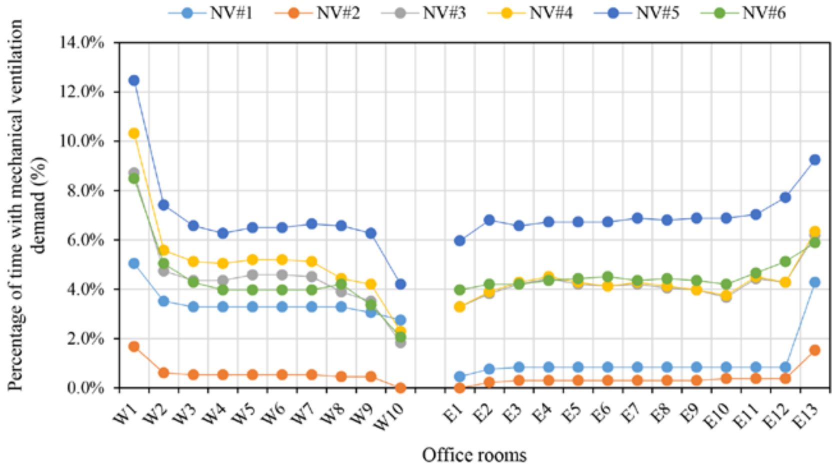


FIGURE 5.10 The percentage of hours when natural ventilation is not enough to provide the minimum fresh air in office rooms (W1-W10: west rooms, and E1-E13: east rooms) for six ventilation strategies in summer (May-September, 2013).

§ 5.5.3.2 Comfort temperature

The average percentage of thermal comfort hours for six ventilation strategies in east and west rooms during the summer months (May-September) is presented in Figure 5.11. According to the simulation results, during the hot periods in summer such as in July big differences exist in the percentage of comfort hours among the ventilation solutions for single skin façades and double skin façades. But when the outdoor air temperature is lower, the results get closer.

The results of Figure 5.12 show that the number of cooling hours is considerably higher in NV#1 (double skin façade with limited external vents) since the vents are not able to remove the excessive heat from the cavity and part of it will be transferred into the rooms and increases the operative temperature inside the offices; hence, leading to the lowest amount of comfort hours during the hot periods (about 75% in July). Improving the size of external vents in the double skin façade in NV#2 minimizes the risk of overheating, so that the number of comfort hours is higher than in NV#1. During the cooler periods, the fresh air is preheated by solar gains in the cavity of the double skin façade before it enters the occupied office spaces. The results show that the average room air temperature is slightly higher in NV#2 compared to other ventilation strategies with a single skin façade; differences are higher in September (1 °C) and smaller in May (0.5 °C). As a result, the number of comfort hours in NV#2 is highest among the ventilation strategies in May and September (and June for east rooms).

Although the total number of comfort hours are quite close for ventilation scenarios with single skin façade, single-sided ventilation combined with cross ventilation through the corridor (NV#4) shows the highest number of comfort hours for office rooms among the strategies. Using an atrium (NV#5) provides the lowest cooling demand however not the highest comfort. Here, the reason for having low cooling demand is because the low-performance atrium was not able to ventilate the rooms during the extreme conditions as much as other scenarios and therefore cool indoor air was not replaced with warm outdoor air.

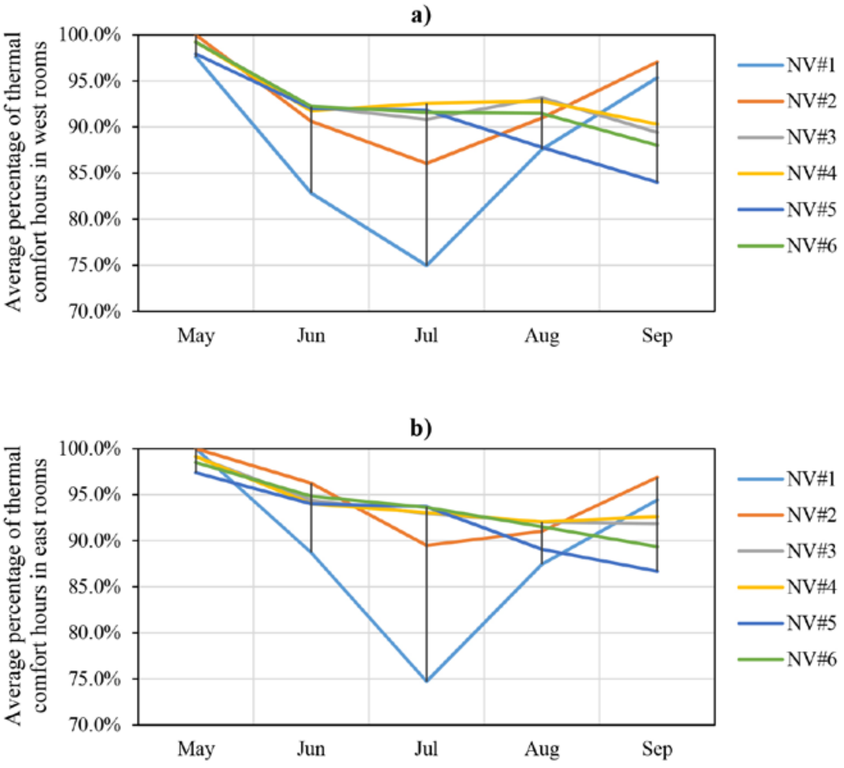


FIGURE 5.11 The average percentage thermal comfort hours for six ventilation strategies during the summer months in: (a) west rooms W1-W10, and (b) east rooms E1-E13.

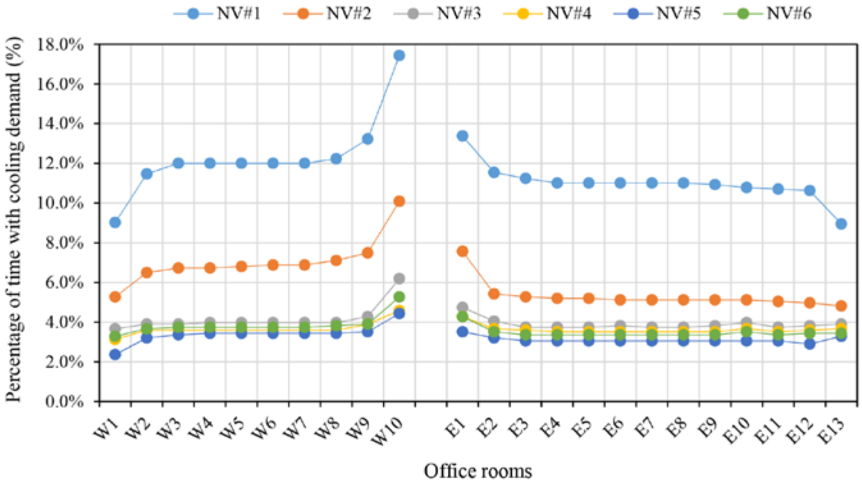


FIGURE 5.12 The percentage of hours when active cooling is necessary to provide thermal comfort in office rooms for six ventilation strategies in summer (May-September, 2013).

§ 5.5.4 Energy saving

Average operative temperatures obtained in west and east rooms for the six ventilation strategies were compared with the comfort temperatures and surrounding limits from the European standard EN15251. The cellular offices that are in direct contact with unventilated spaces such as staircase or plant room have higher indoor air temperatures compared to those located at some distance from the corners. Therefore, the average results for cellular offices that are located in the corners (W1, W10, E1 and E13) were excluded from the comparison. The percentage of hours when the operative temperature in the rooms during occupation was higher than the upper limit for indoor thermal comfort was calculated for the summer months (May-September). During this time, the rooms need active cooling in order to maintain a comfortable indoor temperature. In case of the reference design with air-conditioning system, the percentage of hours when the room air temperature was higher than the adjusted cooling set point temperature (24 °C) was calculated when the system is shut off. Table 5.4 illustrates the percentage of occupancy hours during summer in which the rooms need active cooling.

Due to high internal gains and a low performative cavity (of the DSF) that is not ventilated properly, the reference building needs cooling during almost the entire summer (97-98%) when the building is open. According to Table 5.4, the cooling hours can drop from 98% to 12% by introducing NV through the internal operable windows (30%) while keeping the envelope design the same as the reference building. Generally, NV strategies were able to reduce the cooling demand effectively and approximately within the same range (to only 3% to 7% of active cooling required), except for NV#1. However, reducing the cooling demand does not necessarily mean that the rooms will also be thermally comfortable, specifically when looking at the percentage of comfort hours for the ventilation scenarios with an atrium design (NV#3). The percentage of comfort hours were between 91-93% for NV#3 in the representative rooms. The other percentage of time (4-6%) it would be cooler than the comfort range. Other single skin ventilation strategies provided thermal comfort for the proposed rooms between 93-95% of the time. An atrium design resulted in higher percentage of comfort hours than that in NV#1 (88-89%), but less than that in NV#2 (93-95%).

	REFERENCE	NV#1	NV#2	NV#3	NV#4	NV#5	NV#6
W2-W9	98%	12%	7%	4%	4%	3%	4%
E2-E12	97%	11%	5%	4%	4%	3%	3%

TABLE 5.4 The percentage of occupancy hours in which active cooling is necessary to provide thermal comfort for office rooms located in the western (W2-W9) and eastern (E2-E12) side of the building (May-September, 2013).

§ 5.6 Conclusion

In this paper, the potential use of natural ventilation strategies to reduce the energy demand for cooling and mechanical ventilation was investigated. Six natural ventilation strategies were developed for a 21-storey office building and EnergyPlus combined with the CFD code in DesignBuilder were employed for the purpose of investigation. The study consists of two steps. The air flow rate and the temperature distribution of one floor at mid-level (12th storey) were simulated with the help of Computational Fluid Dynamics (CFD). The CFD simulations were carried out for two distinct temperature and air velocity scenarios in order to predict how they work under different summer conditions. In the second part, the potential of different NV strategies to reduce the energy need for cooling and mechanical ventilation were compared.

TOC

Natural ventilation strategies can provide thermal comfort and fresh air for up to 90% of the occupancy time in summer and therefore can save energy that is generally needed for the operation of traditional mechanical ventilation and air-conditioning systems. Most of the ventilation strategies had almost the same performance except those that were combined with a poorly ventilated double skin façade and the natural ventilation with atrium design.

The double skin façade of the investigated building can easily get too warm or too cold. Therefore, in order to take the most advantage of it, it is necessary to control the operation of vents with the help of a building management system (BMS). Additionally, the minimum temperature set-point for natural ventilation is a major factor for the operation of windows and the thermal comfort within the ventilated space and therefore it should be carefully adjusted according to outdoor temperature variations.

Despite the positive evidence from literature for utilising vertical shafts, our findings showed that natural ventilation strategies that employed stack ventilation by using an atria or solar chimneys had no extra advantages compared to other wind-driven scenarios, considering the air velocity rate or thermal comfort conditions in office rooms. Here two important issues should be emphasised. In this case the building studied features a narrow plan and it is located in a city with high average wind speed throughout the year. As a result, even using simple ventilation methods could achieve the required air changes for reducing the need for mechanical ventilation and cooling. However, stack ventilation has most benefits for buildings with a deep plan when cross ventilation can hardly occur. Furthermore, the configuration of a vertical shaft should be in such a way to provide the temperature variations required to induce buoyancy driven ventilation and to distribute the air flows equally for different floors. Finally, in climates where the wind speed is low and omnidirectional, using vertical shafts might perform better than other ventilation scenarios (single-sided or cross ventilation) since the driving force for the ventilation is not the wind.

Improving or adding natural ventilation strategies to existing buildings are different from new buildings due to the limitations associated with the structure and the architectural plan configuration. For some natural ventilation scenarios, more specifically in case of the atrium design, the performance might be affected under the influence of these design limitations (e.g. size and position of atria). However, the aim of this paper was to study the possible ventilation solutions while having the minimum interference in the existing building's fabric. Moreover, the schedule for the operation of windows were set in accordance with the safety regulations to the occupancy schedule (7:00-19:00). Application of a summer nigh-time ventilation might extend the comfort conditions even to a higher percentage which needs to be investigated when there is no limitation for opening the windows. However, for high-rise buildings it is rarely possible to merely rely on natural ventilation throughout the operating year (Wood & Salib, 2013). It is important to have a supplementary mechanical ventilation system that can be activated when the external conditions are not optimal for using natural ventilation (due to temperature, noise or wind) or in case of design failures (due to changes in architectural design layout or in tenancy patterns). Therefore, a hybrid ventilation system is a way of reducing the risk when natural ventilation may be perceived to be inadequate.

There are some limitations and uncertainties associated with energy simulation tools. One of the uncertainties of this study is related to applied wind pressure coefficient and discharge coefficient values for the calculation of wind-induced pressure and the prediction of airflow through the openings. The wind pressure coefficient is a function of building geometry and site characteristics. Therefore, the specific pressure coefficient data is better to be obtained from wind tunnel measurements. However, this is a very expensive and time-consuming method and therefore might not be applicable if the object that is being tested is too big. Furthermore, the discharge coefficient (C_d) is a function of window characteristics (opening angle and the ratio between the length and the width of the opening) and the flow direction. In preliminary design calculations or in the absence of actual values, a generally used value for the discharge coefficient of a sharp-rimmed large opening is C_d=0.6 ± 0.1 (Flourentzou et al., 1998). In this study, a default discharge coefficient of 0.65 is used for windows and holes (Dols & Walton, 2002). Considering other uncertainties in natural ventilation calculations such as wind pressure coefficients, effective areas of real-world openings and crack flows, using a discharge coefficient between 0.60 and 0.65 should provide sufficient accuracy (DesignBuilder).

The DesignBuilder's CFD code has limitations in defining graphically the air flows through the cracks; however, porous flows can be calculated in EnergyPlus. Therefore, importing the air flows from EnergyPlus that include the crack leakage can cause serious flow imbalance problems (DesignBuilder). To avoid this problem the effect of infiltration is excluded from air flow calculations. Furthermore, for summertime simulations the effect of infiltration would be insignificant as compared to flow rates from the vents, holes and open windows.

In this study, natural ventilation is operated by automated windows. It means that natural ventilation is possible when the room temperature is within the predefined temperature set points and the offices are occupied. Therefore, the whole office uses only one threshold to trigger opening and closing actions. To make the model appears like a real situation for window operation, future studies can introduce different set points for opening and closing to include the occupant's interaction with windows.

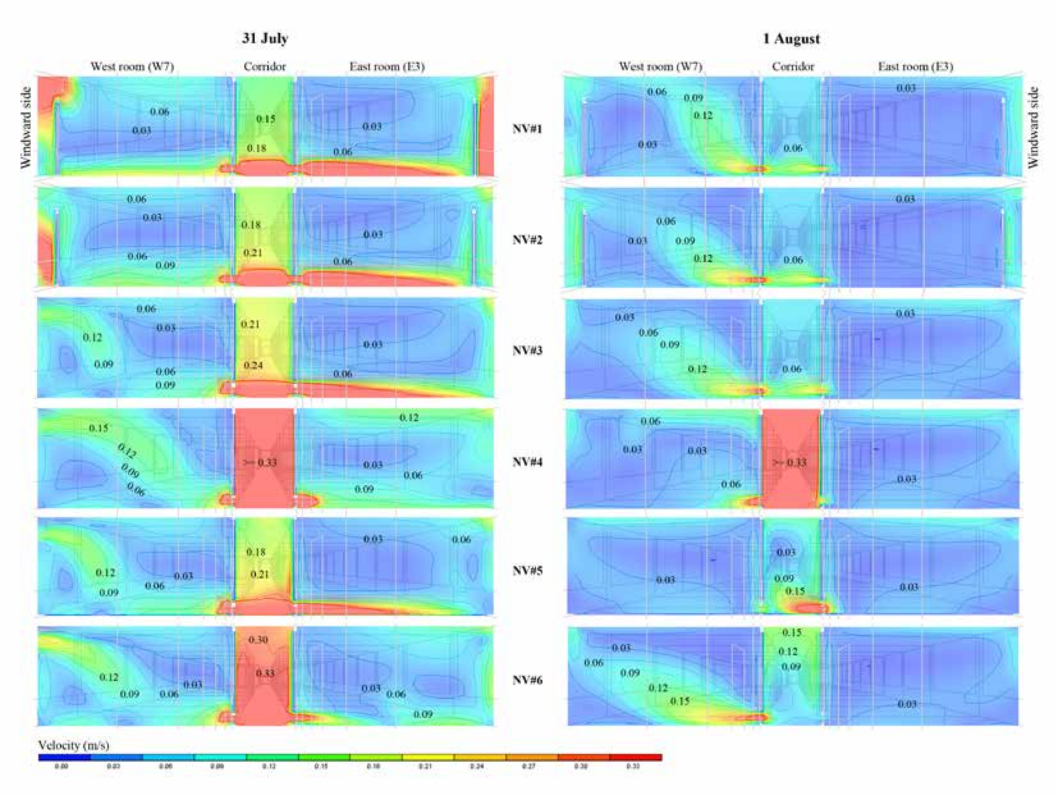


FIGURE 5.13 A vertical section of air velocity across the rooms W7-E3.

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PART B / TROPICAL CLIMATE

§ 5.7 Tropical climate: KOMTAR building

This study is a follow-up of chapter 4 regarding energy-saving solutions for the envelope design of high-rise buildings in tropical climates. In the first part, energy-saving measures such as shading elements, glazing type, window-to-wall ratio (WWR), service core placement and roof design were investigated with a special focus on cooling and electric lighting. For this purpose, the KOMTAR tower was selected as a conventional design for tall office buildings in the tropical climate and the energy use prior to and after refurbishment was compared through computer simulations with DesignBuilder version 4.7. DesignBuilder is a powerful interface that incorporates the EnergyPlus simulation engine to calculate building (energy) performance data. The simulation model in DesignBuilder was validated using metered energy data of the KOMTAR building in 2004.

The follow-up study presented here aims to address the potential use of natural ventilation (NV) as a replacement for or supplement to mechanical ventilation using the base validated model of the KOMTAR building. In order to minimise the impact of the reference building’s poor performing envelope on the results of the investigation, two external envelope measures have been upgraded. Their selection was based on our findings from the previous chapter that showed these two envelope aspects have the highest influence on building’s energy performance. For the simulation model, the single pane 6 mm clear glass of the reference design is therefore replaced with double-glazed spectrally selective glazing. Additionally, external shading elements (louver and overhang) are employed as a replacement for the reference building’s low-performance indoor blinds.

TOC

§ 5.7.1 Building design

The KOMTAR tower is a 65-storey commercial building with a conventional design that uses air-conditioning system year-round for providing comfort conditions for the occupants. The building has a twelve-sided plan shape that measures 60 m from façade to façade. The building features an open-plan layout and a central service core, as shown in Figure 5.14. From the total gross floor area on each floor (2894 m^2), the share of the service core is around 22%. The service core houses lift lobbies, stairways and sanitary spaces. The 12-sided central core is enclosed by three banks of lifts and is only open on three sides where the office zone is connected to the corridor; one on the north, one on the south-east, and one on the south-west. The building has a high percentage of glazing that is evenly distributed across the external façade on all orientations and accounts for 80% of the external envelope surface area.

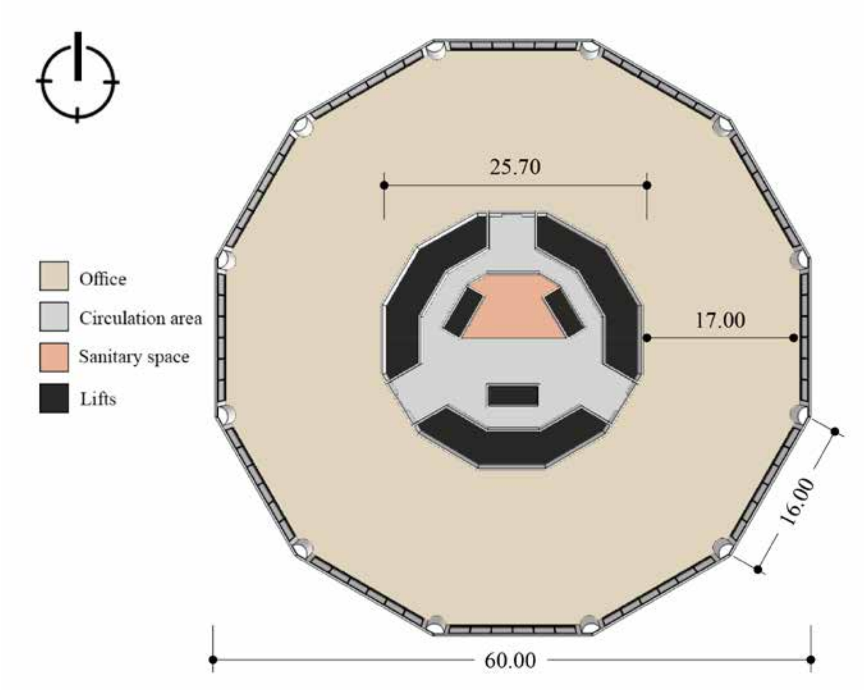


FIGURE 5.14 A simplified typical floor plan of the KOMTAR tower.

§ 5.7.2 Climate

The KOMTAR tower is located in George Town, a city in Malaysia with a tropical climate (Latitude 5°17´N and Longitude 100° 27´E). This climate features high daily mean air temperatures and a high relative humidity throughout the course of the year. The climate of this region is influenced by the proximity to the equator and the surrounding sea; this results in relatively small annual temperature variations, considerable humidity and occasionally high wind speeds. The annual average day-time and night-time temperatures is 29.3 °C and 26.8 °C respectively (Figure 5.15). Winds may blow from all directions but the pre-dominant wind direction is north and the annual average wind speed is around 1.5 m/s (Figure 5.16). Occasionally, during the monsoon seasons (May-September and November-March) wind speeds of up to 6 m/s can be expected from south-west or north-east. During the course of the year, the humidity fluctuates in a range between 60 – 90%. For this study, weather data were obtained from the nearby Bayan Lepas weather station at Penang Airport (20 km south-west of the location) (US Department of Energy). Since the energy consumption data measured were obtained in 2004, the weather data were also acquired from 2004.

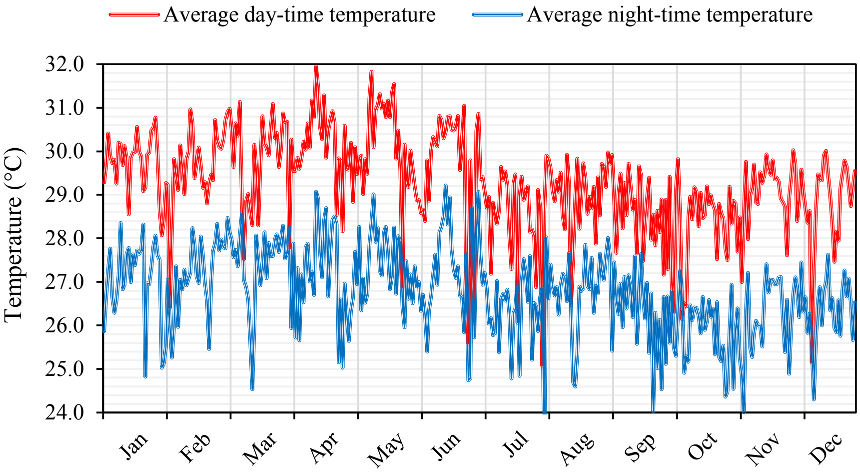


FIGURE 5.15 The average daily values of the dry-bulb temperature for day-time (7:00-19:00) and night-time (19:00-7:00) at Penang Airport in 2004.

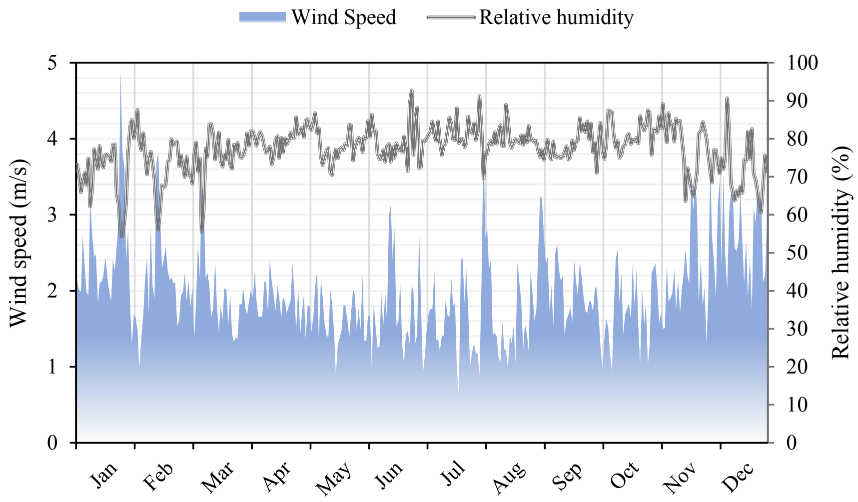


FIGURE 5.16 The daily values of wind speed and relative humidity at Penang Airport in 2004.

§ 5.8 Methodology

The objective of this study is to determine the potential use of natural ventilation (NV) as a replacement for or supplement to mechanical ventilation for high-rise office buildings in the tropical climate. For this purpose, three natural ventilation strategies were developed for the base case by changing several design parameters including the size of air inlets/outlets (the percentage of operable window area), and the application of vertical shafts. Through the application of different ventilation strategies, this research aims to address the following questions:

- What percentage of office hours can natural ventilation provide sufficient fresh air in the office area?
- What percentage of office hours can natural ventilation provide enough cooling to keep the indoor temperature in the office areas within the (adaptive) comfort range?
- Among the considered alternatives, which of the natural ventilation strategies can improve the comfort area (and the energy performance) in the office zone more than others?

In this study, the investigation of NV strategies comprises of two main steps, as shown in Figure 5.17. In the first step, the amount of fresh air changes per hour and the operative temperature is calculated during one year (2004). The EnergyPlus calculation engine within DesignBuilder simulation software was used to run the calculations. For this purpose, three office floors at different heights (low-, mid- and top-level) were selected and the results of the simulation were used to calculate the percentage of the occupancy time during which comfort conditions can be provided by the application of NV. These results were assessed according to the ASHRAE 62.1 standard (ASHRAE, 2004) and the adaptive thermal comfort model for calculating the minimum fresh air requirements and the higher limit of comfort temperature respectively. The number of discomfort hours during the occupancy time in one year determines the number of hours that active cooling or mechanical ventilation is necessary to provide comfort conditions on the test floors. A lower number of discomfort hours means that the ventilation strategy performs better, hence saves more energy.

In the second step, the CFD code in DesignBuilder was used to compare the air velocity and temperature among the three NV strategies on the proposed three office floors under three different weather conditions: no wind (0 m/s), average wind speed (1.5 m/s) and high wind speed (6.0 m/s). The average and maximum indoor air velocities, as well as the office floor area with an indoor operative temperature higher than the upper comfort limit were calculated. Then Szokolay's physiological cooling equation (Auliciems & Szokolay, 2007) was employed to measure the potential cooling effect of elevated air velocities for different NV strategies. Finally, the increased area of comfort (%) due to elevated air flow for the 27 CFD simulations was calculated and compared with the reference design.

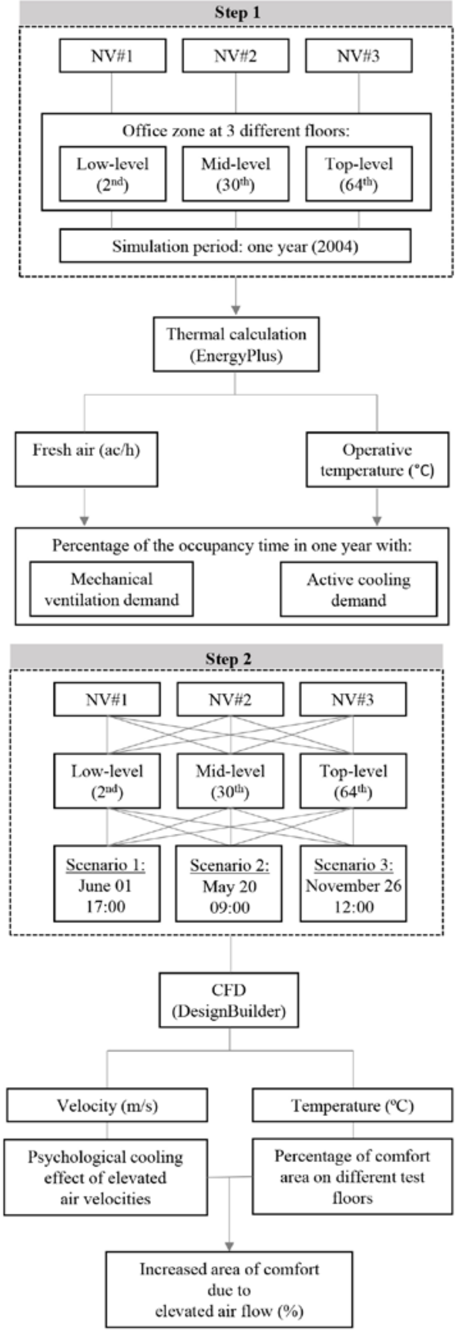


FIGURE 5.17 Methodological scheme of research.

§ 5.8.1 Fresh air calculation

For the proposed NV strategies, it is assumed that the external windows are controlled entirely by a schedule and are not affected by temperature controls or occupants. Therefore, all the external openings are constantly open during the occupancy hours (8:00 – 17:00) for the operation of NV. The building- and occupancy-related parameters with selected values used for the simulations are summarised in Table 5.5.

PARAMETER	VALUES
External wall insulation (U-value)	2.05 W/m^2-K
Roof insulation (U-value)	2.13 W/m^2-K
Glazing type	Dbl LoE Spec Sel Clr 6mm/13mm Arg
U-value of glass	1.34 W/m^2-K
SHGC of glass	0.42
Light transmission of glass	0.68
Shading	Combined external shading devices: Overhang (1 m) + Louver (0.5 m)
Metabolic rate	0.9 met (average value for men and women)
Occupancy density	0.1 person/m^2
Occupancy schedule	7:00 – 19:00 h (Mon-Fri)

TABLE 5.5 Building and occupancy parameters and the proposed values for the simulation.

According to the ASHRAE Standard 62.1-2004 (ASHRAE, 2004), the fresh air minimally required for light office work is around 8.5 l/s per person. For the purpose of the fresh air calculation, the occupancy density was assumed to be 0.1 person/m^2. This is equivalent to 222 people per office floor (2223.6 m^2). Therefore, a total amount of 1887 l/s (222×8.5) of fresh air is needed to ventilate 7382 m^3 of space. This means that the office zone at each floor requires a minimum of 0.92 ac/h to provide enough fresh air for the occupants. The total amount of fresh air changes per hour in the office zone was simulated in EnergyPlus for different NV strategies. The percentage of hours in which the air change rate was equal to or higher than this minimal value was obtained for the three ventilation strategies for the year 2004.

§ 5.8.2 Comfort temperature calculation

The impact of ventilation strategies on the occupants' thermal comfort during one year (2004) was assessed using the adaptive equations for thermal comfort in free running buildings from the European standard EN15251 (European Standard EN15251, 2007). Two comfort temperature ranges were selected with 80% and 90% acceptability limits. The 80% acceptability limit introduces a bandwidth around the comfort temperature of ±3 K, while the 90% acceptability limit covers a narrower bandwidth around the comfort temperature of ±2 K. The average percentage of the hours with thermal comfort was assessed for the three ventilation strategies in the proposed test floors, based on these 80% and 90% acceptability limits.

§ 5.8.3 Computational Fluid Dynamics (CFD)

As an alternative, the CFD technique was employed to have a more detailed examination of the velocity and temperature distribution inside the KOMTAR building at three different heights, and under three different wind scenarios. The CFD simulations were carried out for three distinct scenarios: a typical condition and two extreme conditions (see Table 5.6). The first scenario (01 June, 17:00) represents a typical day with an outdoor air temperature of 29.5 °C and wind (speed: 1.5 m/s) coming from the prevalent direction (north). The performance of the NV strategies was also tested for two extreme weather conditions: 0 m/s wind speed (20 May, 9:00) and 6.0 m/s wind speed (26 November, 12:00). Since the air flow patterns might be affected by variations in temperature between the inside and outside, the time snaps were selected on three distinct times during a day; morning, mid-day, and evening.

According to the yearly wind rose diagram at Penang Airport, a wind speed of 1-2 m/s from the north is the most frequent throughout the course of the year while for higher wind speeds (such as 6.0 m/s), the south-west is the dominant direction (see Figure 5.18).

WEATHER SCENARIO	Date / time	Outdoor dry-bulb temperature (°C)	Wind speed (m/s)	Wind direction (degree)
S.1. Typical condition	01 June / 17:00	29.5	1.5	360 (N)
S.2. No wind	20 May / 9:00	29.0	0.0	---
S.3. High wind	26 November / 12:00	30.0	6.0	225 (SW)

TABLE 5.6 The proposed weather scenarios for CFD simulations.

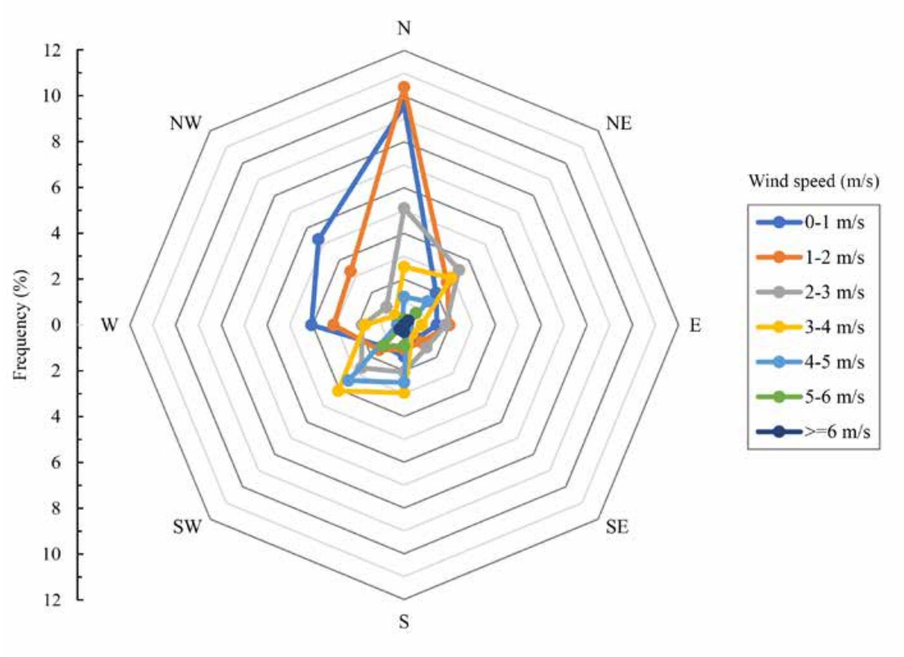
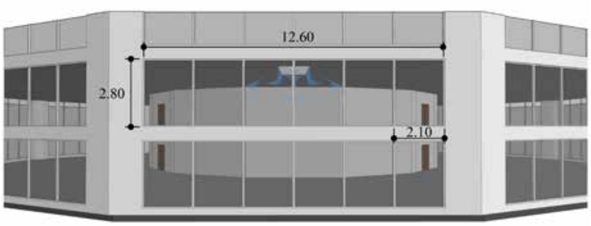


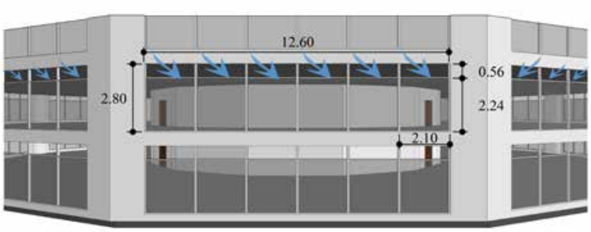
FIGURE 5.18 Frequency distribution of wind speed and direction at Penang Airport in the year 2004.

§ 5.8.4 Proposed natural ventilation strategies

In the KOMTAR building (reference design), the external windows are not operable and the building fully relies on fans and air-conditioning for providing comfort conditions. On a typical floor, each group of windows located on one side of the dodecagon has a size of 12.6 × 2.8 m (W × L) and is located 0.7 m above the floor in the centre of the external wall (Figure 5.19a). In order to provide natural ventilation for this building, the fixed external windows are changed to operable windows. The position of the aperture of all operable windows is located at the top and the aperture size is 20% of the total window area. The air flow opening is assumed to be a gap in the window. This means that 7 m^2 of window area – on each side of the plan – can be opened for the purpose of ventilation (Figure 5.19b).



(a) Fixed external windows in the reference design



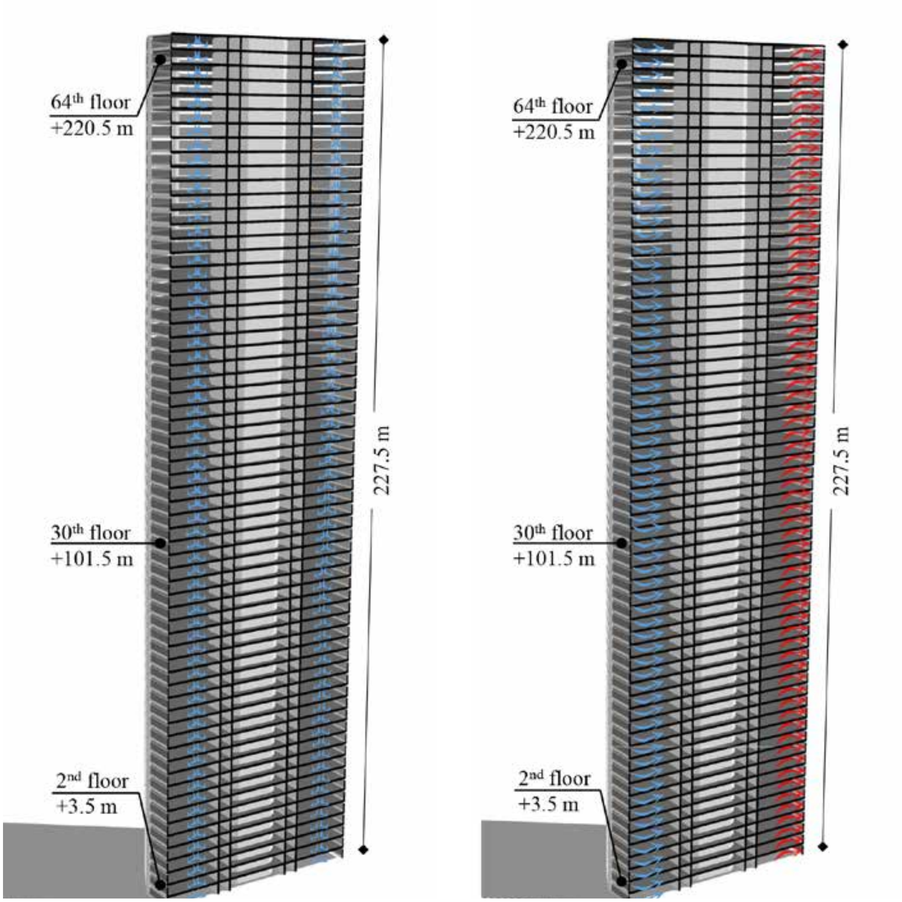
(b) 20% operable external windows for natural ventilation

FIGURE 5.19 The size of external windows and the openable window area.

In this study three different ventilation strategies were developed for the base case using cross or stack ventilation or a combination of them. A visual representation of the three ventilation strategies and of the reference building, along with the intended air flow patterns across the ventilated spaces, are provided in Figure 5.20. Vertical distances between the investigated floors and ground level are measured at around 3.5 m for the base-level (2nd), 101.5 m for the mid-level (30th), and 220.5 m for the top-level (64th).

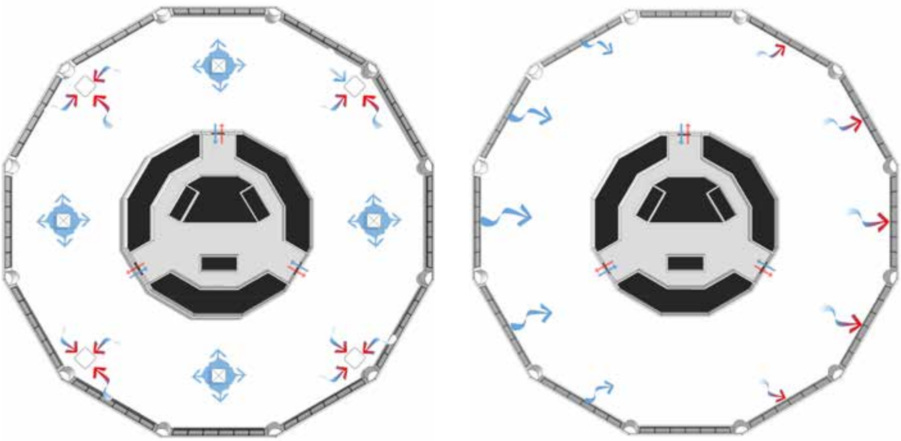
For the reference design, the HVAC system delivers the cool supply air from the area above the suspended ceiling into the office zone (Figure 5.20a). In NV#1: cross ventilation, the main driving force for ventilation is wind. Fresh air can enter the building through the operable windows on the windward side and exit the building from the external openings on the leeward side (Figure 5.20b). The potential of stack ventilation through the application of a vertical shaft is tested in NV#2 and NV#3. For this purpose, an atrium (3.3×5.4 m) is added in the centre of the service core with an exhaust opening at its top. A 3-storey extension is also added on top of the roof which has the same floor area as the service core. This extension is added with the aim of improving the air extraction and reducing high temperatures in the top floors. On lower floors, the outdoor air is expected to enter the building through the 20% of the operable window area along the external façade. The stale air is then sucked into the corridor, pulled up through the vertical shaft, and finally escapes the building through the operable windows on the outer façade perimeter of the rooftop extension of the central core. The external façade of this extension has large openings on all sides and the window-to-wall ratio (WWR) is set to 80%, while only 20% of the total window area can be opened for ventilation as shown in Figure 5.21a.

The impact of the shaft's height on natural ventilation is tested for a full height and a segmented atrium. In NV#2, the vertical shaft is extended along the entire building height (Figure 5.20c). In NV#3, the atrium has a segmentation at mid-height (34th storey). A 3-storey wind floor (on top of the 30th floor) divides the vertical shaft in two parts that are isolated from one another (Figure 5.20d and Figure 5.21b). In order to minimise the resistance, the air flow encounters between the office zone and the service core, big openings (4.80×3.20 m) are created on three sides along the core perimeter. The size of the external windows and the openable area on the rooftop extension and on the wind floor are presented in Figure 5.21.



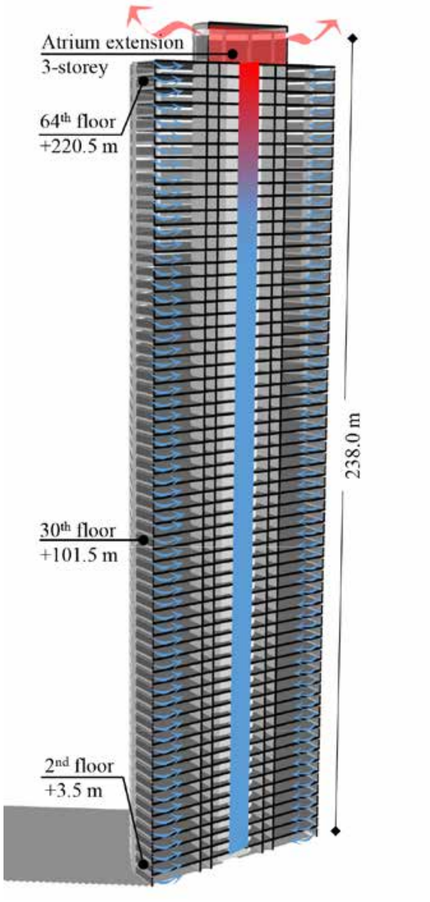
(a) Reference: mechanical ventilation

(b) NV#1: cross ventilation

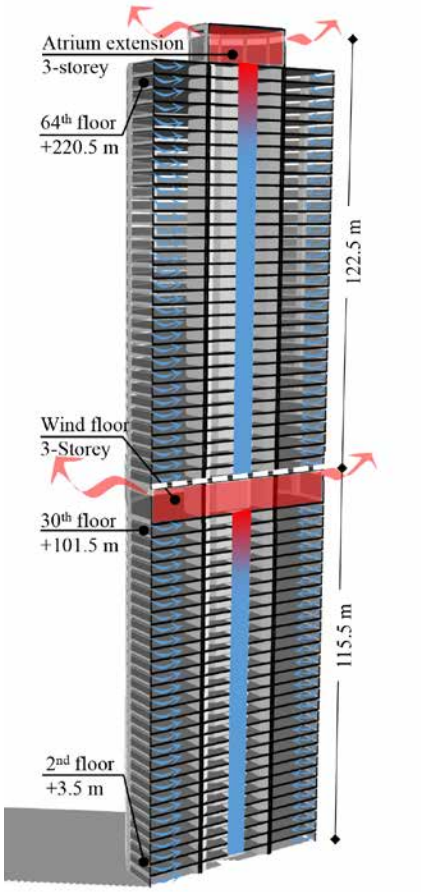


Typical floor plans (reference)

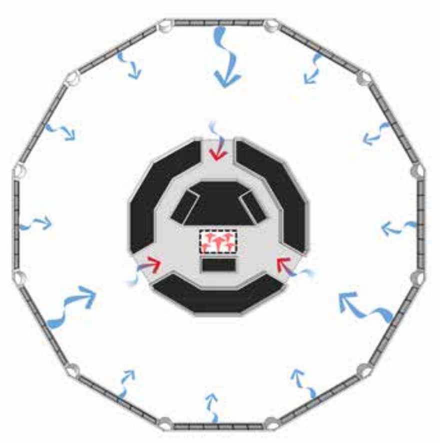
Typical floor plans (NV#1)



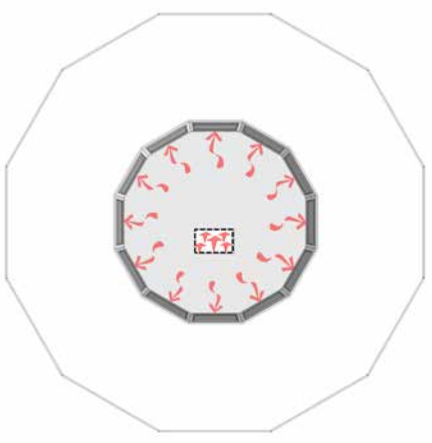
(c) NV#2: stack ventilation



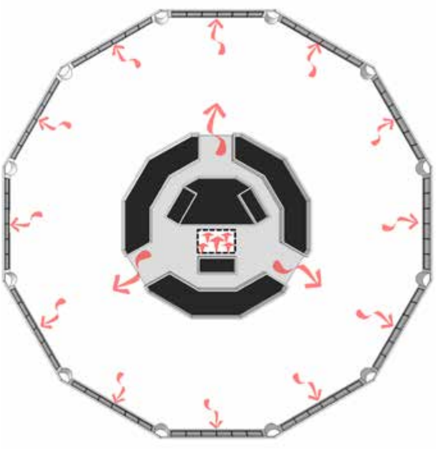
(d) NV#3: stack ventilation



Typical floor plans (NV#2 & NV#3)

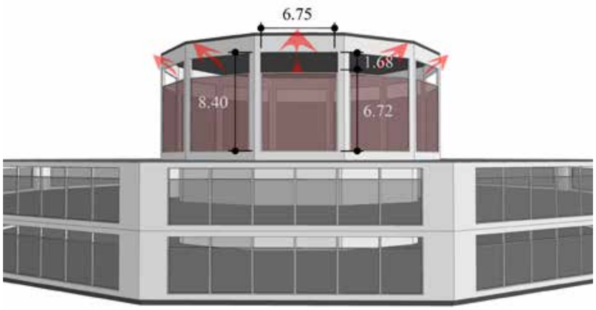


Atrium extension (NV#2 & NV#3)

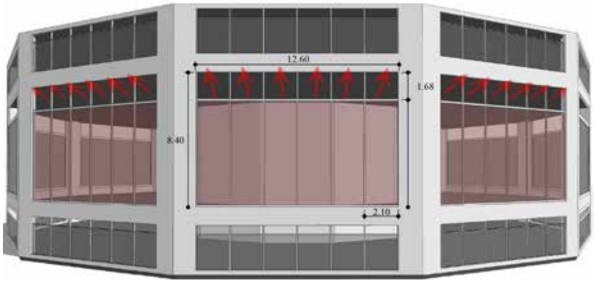


Wind floor (NV#3)

FIGURE 5.20 Proposed ventilation strategies and the reference design. Arrows show the intended flow pattern within the ventilated spaces on a typical floor plan and through the building height.



(a) Rooftop extension of the central core in NV#2 & NV#3 (20% operable external windows)



(b) Wind floor in NV#3 (20% operable external windows)

FIGURE 5.21 The size of external windows and the openable area on (a) rooftop extension, and (b) wind floor.

§ 5.9 Results and discussion

§ 5.9.1 Indoor comfort

Thermal comfort and fresh air are among the main indoor comfort indicators. Using natural driving forces, comfort conditions can be improved to a different extent depending on the design and local weather conditions. Three ventilation strategies were simulated in the EnergyPlus calculation core of DesignBuilder. The amount of discomfort hours during the occupancy time in one year determines the number of hours that active cooling or mechanical ventilation is necessary to provide comfort conditions on the test floors. A lower number of discomfort hours means that the ventilation strategy performs better, hence saves more energy.

§ 5.9.1.1 Fresh air changes

The percentage of hours in which the ac/h was equal to or higher than the minimum required value (0.92 ac/h) was obtained for the test floors (2nd, 30th, and 64th) at different heights, as shown in Table 5.7. This table shows the percentage of time during office hours (8:00 – 17:00) in which natural ventilation alone can meet the minimum requirement for fresh air and, therefore, supplementary mechanical ventilation is not needed. Windows are scheduled to be constantly open during the occupancy time. It is probable that when the required fresh air cannot be generated it is due to low wind speed and the failure of the NV strategy to increase the flow rate in such conditions.

NV STRATEGY	Base floor (2nd)	Middle floor (30th)	Upper floor (64th)	Average value
NV#1	90.4%	99.9%	100%	96.8%
NV#2	99.8%	100%	96.8%	98.9%
NV#3	100%	100%	99.5%	99.8%

TABLE 5.7 The percentage of hours when natural ventilation can provide the minimum fresh air on the test floors for three ventilation strategies in the year 2004.

The simulation results for the ventilation strategies are quite promising. The need for mechanical ventilation is reduced to less than 4% of the occupancy hours when taking the average value of the three test floors, while no test floor has a value lower than 90%. The need for mechanical ventilation is different depending on the location of the test floor and the driving force for natural ventilation. The results show that NV#3 and NV#2 can provide the minimum fresh air requirement during a higher percentage of occupancy time. This can be attributed to the application of a vertical shaft that enhances supply of fresh air in a calm day with no particular wind. The best performance, however, is achieved by using a natural ventilation strategy with a segmented atrium (NV#3). Segmenting the atrium can minimise the variation of the fresh air entry rate on different floors (Etheridge & Ford, 2008), as compared to a full-height atrium. The results show that the top floor of a building that employs a full height atrium (NV#2) needs supplementary mechanical ventilation during a higher percentage of occupancy time (about 3%) than a segmented atrium. However, the segmentation of the vertical shaft may limit the full effect of buoyancy and result in a reduction of indoor air velocity on particular levels.

Among all ventilation strategies, the base floor (2nd) in NV#1 is in highest demand for mechanical ventilation by around 10% of the occupancy hours, while there is no need for a supplementary mechanical system on the middle and upper floors (30th and 64th). In NV#2 and NV#3, the top floor (64th) needs mechanical ventilation for a higher percentage of occupancy time. When the stack effect is the dominating driving force for natural ventilation (in the absence of wind), the air that enters the upper floor comes from the shaft and is therefore stale air. As a result, it could be questionable to use this air as fresh air. In such conditions, the integration of sky gardens into atrium -for air supply and exhaust- and segmentation of atrium along the building height are passive strategies that can effectively reduce stale air accumulation on the upper floors. When comfort conditions are not achievable through passive techniques, an assistant mechanical ventilation system besides natural ventilation might be essential for certain floors depending on the physical mechanism driving the air movement during some periods in the course of a year in the tropical climates; the lower floors of a building with a wind-induced ventilation strategy, and the middle floors (and the upper floors) of a building with a buoyancy-induced ventilation strategy. The 3% higher demand for mechanical ventilation on the top floor compared to the middle floor of this building with a full height atrium is probably caused by design specifications of this particular building; otherwise it is generally expected to have lower air exchange through the windows at the height close to the neutral pressure plane.

TOC

§ 5.9.1.2 Comfort temperature

The average percentage of thermal comfort hours is calculated for the proposed NV strategies at different test floors in one year. The results are presented for two sets of acceptability limits as shown in Figure 5.22. The 80% acceptability limits are for normal expectations that introduce a boundary around the comfort temperature of ±3 K. When a higher standard of thermal comfort is desired, the 90% acceptability limits can be used that involve a narrower comfort temperature range of ±2 K.

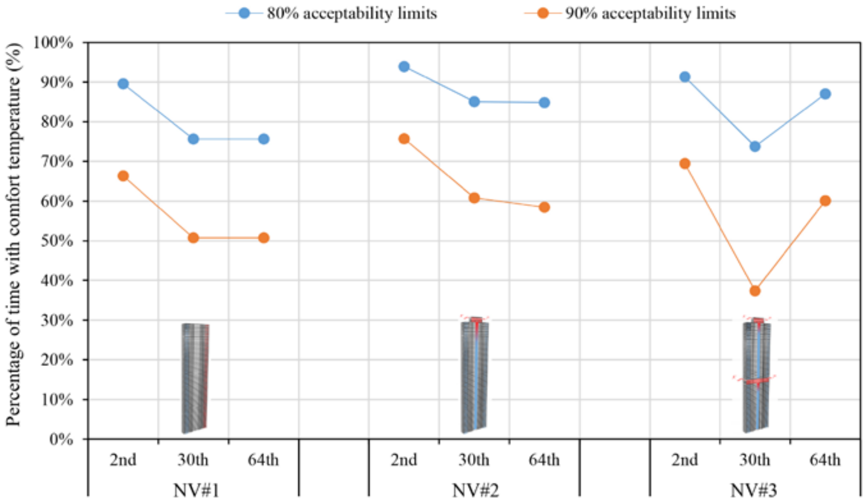


FIGURE 5.22 The average percentage of thermal comfort hours for three ventilation strategies on the proposed test floors based on 80% and 90% acceptability limits.

If the wider comfort temperature range (±3 K) is selected, natural ventilation strategies will be able to keep the indoor temperature within the comfort limit during the majority of occupancy hours (ranging from 74% to 94%). Depending on the location of the test floors, in NV#1, the number of comfort hours is between 76%-90%. The results show that adding a vertical shaft into the central core (NV#2 and NV#3) can extend the percentage of comfort hours by up to 10%. The highest number of comfort hours is achieved by using a full height atrium (NV#2). The three test floors, in NV#2, have a temperature which is comfortable for 85-94% of the occupancy time. For the same ventilation scenario, these figures will reduce to a range between 58-76% if the narrower comfort temperature range (±2 K) is selected.

In NV#2 and NV#3, the heat stratification through the vertical shaft results in higher indoor temperatures on the upper floors in comparison with the lower zones. For this reason, the upper floors have a lower percentage of comfort hours. In NV#2, the percentage of comfort hours on the top-level is lower than on the base-level by around 9% and 18% respectively, with 80% and 90% acceptability limits. Generally, for all NV strategies, the middle floors have thermal conditions almost similar to the upper floors, with the exemption of NV#3. In NV#3, the middle floor is directly located under the wind floor level where the atrium is segmented, and therefore the indoor air temperature on this floor is highly influenced by the high temperatures of the floor above it and the warm stale air that enters this floor through the shaft. As a result, the mid-floor has the lowest percentage of comfort hours among the three test floors in NV#3. With the narrower comfort temperature range, the percentage of comfort hours for the mid-level in NV#3 is 14% less than in NV#1, and 24% less than in NV#2. In NV#3 with a segmented atrium, the number of comfort hours on the upper test floor is higher than on the middle one. This can be explained by a further distance (one storey or 3.5 meter) between the 64th storey and the location of air outlets on top of the vertical shaft (at atrium extension level) as compared to the 30th storey which is located in close proximity to air outlets on the wind floor. In NV#3, the top floor has the highest value of comfort among the top-floors in all NV strategies. This shows that segmentation of the vertical shaft might reduce the uncomfortable conditions on the upper floors. However, it is important to increase the height of the wind floor to more than 3 stories (10.5 m) or add more segmentations along the building height to lessen the effect of heat stratification on the top floors and to reduce the wind speeds inside the atrium.

When the outdoor air temperature is higher than the indoor air temperature, higher fresh air changes can cause lower number of comfort hours, and vice versa. In NV#1, the base floor has a higher percentage of comfort hours, which can be related to inefficiency of this ventilation scenario in an increasing velocity and fresh air supply at this floor. This is in line with the results of fresh air calculation that is presented in Table 5.7 (Section 6.8.1.1).

§ 5.9.2 Air flow patterns and indoor air temperature

The following section includes a detailed investigation on the NV strategies by using the CFD code in DesignBuilder. Under three weather scenarios, velocity and temperature simulations were carried out on the working planes at a height of 1.2 meter above the floor; again the 2nd, 30th and 64th floors were analysed. Accordingly, the average and

TOC

maximum value of air velocity, and the percentage of floor area –excluding the service core – with an indoor air temperature higher than the upper comfort temperature range (based on 90% acceptability limits) was calculated for the three test floors. The comfort temperature was calculated using the adaptive equations for comfort in free running buildings (see Table 5.8).

WEATHER SCENARIO	T_{out} (°C)	T_{comf} (°C)	$T_{comf-upper}$ (°C)
01 June / 17:00	29.5	28.0	30
20 May / 9:00	29	28.0	30
26 November / 12:00	30	28.1	30.1

TABLE 5.8 The outdoor air temperature (T_{out}), comfort temperature (T_{comf}), and the upper limit of the comfort temperature ($T_{comf-upper}$) based on the narrower comfort temperature range for the three weather scenarios.

Since each category of air velocities has a different percentage value (of discomfort area), the weighted average method was used to calculate the average velocity on the working planes. In order to calculate the average weighted value, each category value (of air velocities) was multiplied by its percentage (of its share from the total area) and then all the values were added together. In this study, the internal surface temperatures for each surface in the domain and the airflow rates through open windows, vents, doors and holes were calculated first using an EnergyPlus simulation which was then imported as boundary conditions for the internal CFD analysis. Generally, in hot and humid climates, an indoor air movement of up to 1 m/s is pleasant. Even higher velocities may be perceived as acceptable by the occupants as they can help to extend the comfort temperature limits (Szokolay, 1997).

§ 5.9.2.1 Scenario 1 (average wind speed)

The first scenario represents a typical weather condition in George Town: a wind speed of 1.5 m/s coming from the prevalent direction (north) and an outdoor air temperature of around 29.5 °C. w 5.23 shows the air velocity and the temperature contours for different natural ventilation scenarios on three test floors at different levels: base level (2nd floor), mid-level (30th floor), and top-level (64th floor). In NV#1, the pressure differentials between the openings on the windward and leeward sides are the driving force for natural ventilation. However, the floor plates are too deep for natural ventilation to reach deep zones. Therefore, the areas of higher velocities would be limited to the office zones that are located between the external windows and the service core on the northeast and northwest of the floor plan. Moreover, the pressure

TOC

across the envelope increases at higher altitudes, therefore the top floors exhibit higher indoor air velocities. On the upper floor level and mid floor level in NV#2 and NV#3, the fresh air flows in through the openings on the windward side (north) and flows out mostly thought the openings on the leeward side and partially through the atrium. The results show there is a downward flow through the atrium, so that part of the used air of the upper levels flows into the lower levels through the vertical shaft. A reverse stack effect occurs when the outdoor air temperature is higher than the indoor air temperature (Wood & Salib, 2013). The existence of this reverse flow could deteriorate the indoor air quality, especially for offices in the lower zones of the building. This scenario thus leads to a combination of cross ventilation with a small amount of reverse stack ventilation.

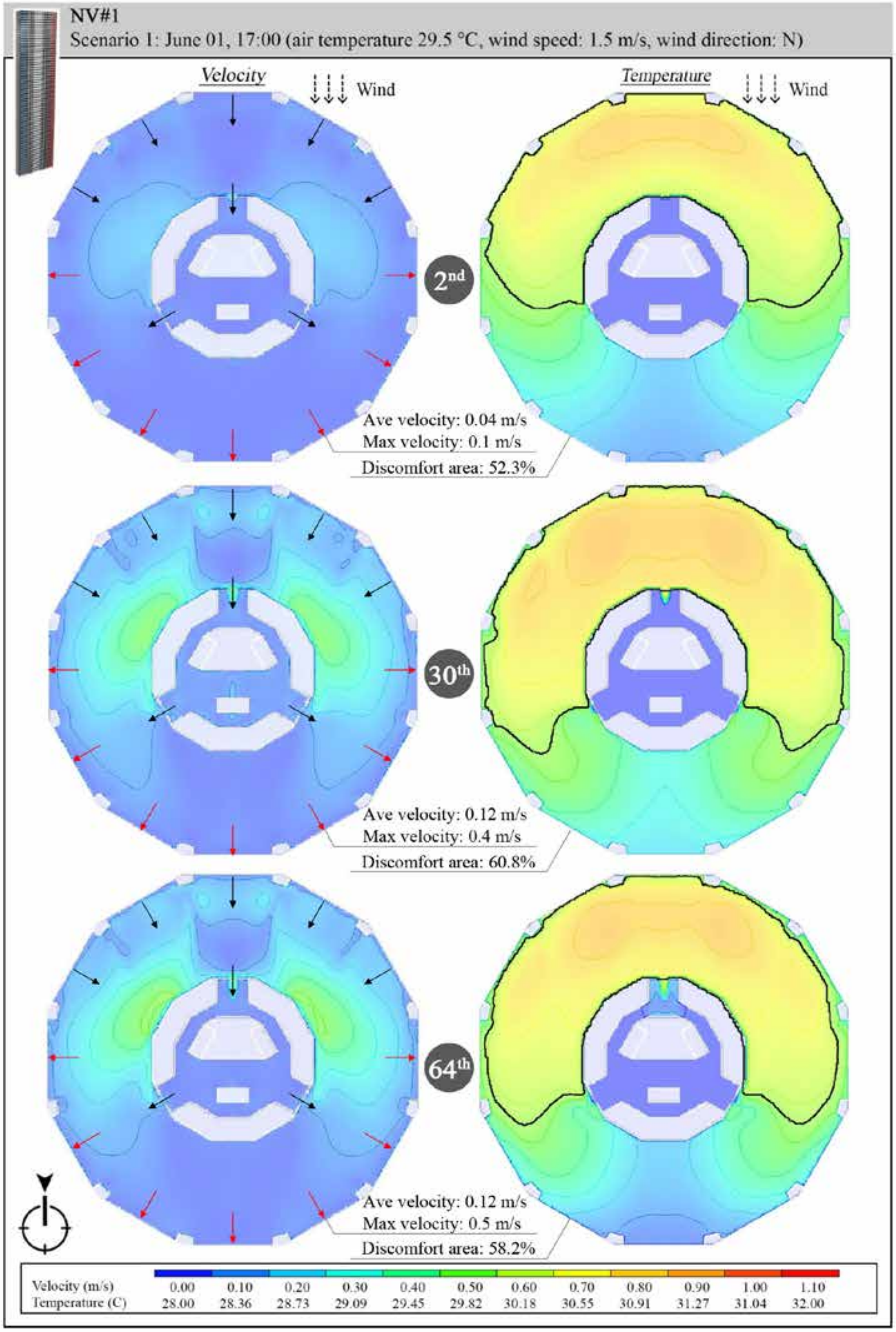
According to the CFD results, the average air velocities on the working planes are in a range of 0.04-0.12 m/s in NV#1, 0.11-0.13 m/s in NV#2, and 0.09-0.12 m/s in NV#3. In regards to average air velocities (on the middle and upper floors in particular), no significant differences are found between the performance of ventilation strategies with or without a vertical shaft, under typical weather conditions. This is due to a number of reasons such as small differences between indoor and outdoor air temperature (and therefore limited stack effect), and presence of wind (1.5 m/s). The combination of these factors makes the buoyancy force play a minor role in driving the natural ventilation. The maximum velocities on the base floor (2nd) in NV#2 and NV#3 are nine times of the maximum velocity on the equivalent floor in NV#1 due to the formation of pressure gradients along the vertical shaft. However, the air distribution is not uniform throughout the entire plan and there are areas with particularly higher velocity such as in the corridor openings and their adjacent external windows. Slight differences can be observed between the performance of a full-height and a segmented atrium. The application of a full-height atrium (NV#2) can increase the average velocity slightly more than a segmented atrium design (NV#3); by around 0.02 m/s for the base floor and around 0.01 m/s for the top floor.

The CFD study of the temperature distribution shows that areas of the office zone close to the external windows on the northern part of the plan, where fresh air is entering the building, have a higher temperature that exceeds the upper limit of the comfort range (30 °C) in weather scenario 1. In NV#1, the average discomfort percentage is about 60% which is almost within the same range among all floors at different heights. In NV#2 and NV#3, the majority of office areas on the base floor are within the comfort range. In a full-height atrium, the agglomeration of heat on the top levels causes the highest percentage of discomfort (100%) to be formed on the upper floor. In NV#3, both the 64th and 30th floors are located at close distance from the air outlets of the vertical shaft. As a result, the middle floor has the same comfort conditions as the top floor in NV#3, with almost the entire apace within the discomfort range. Our findings

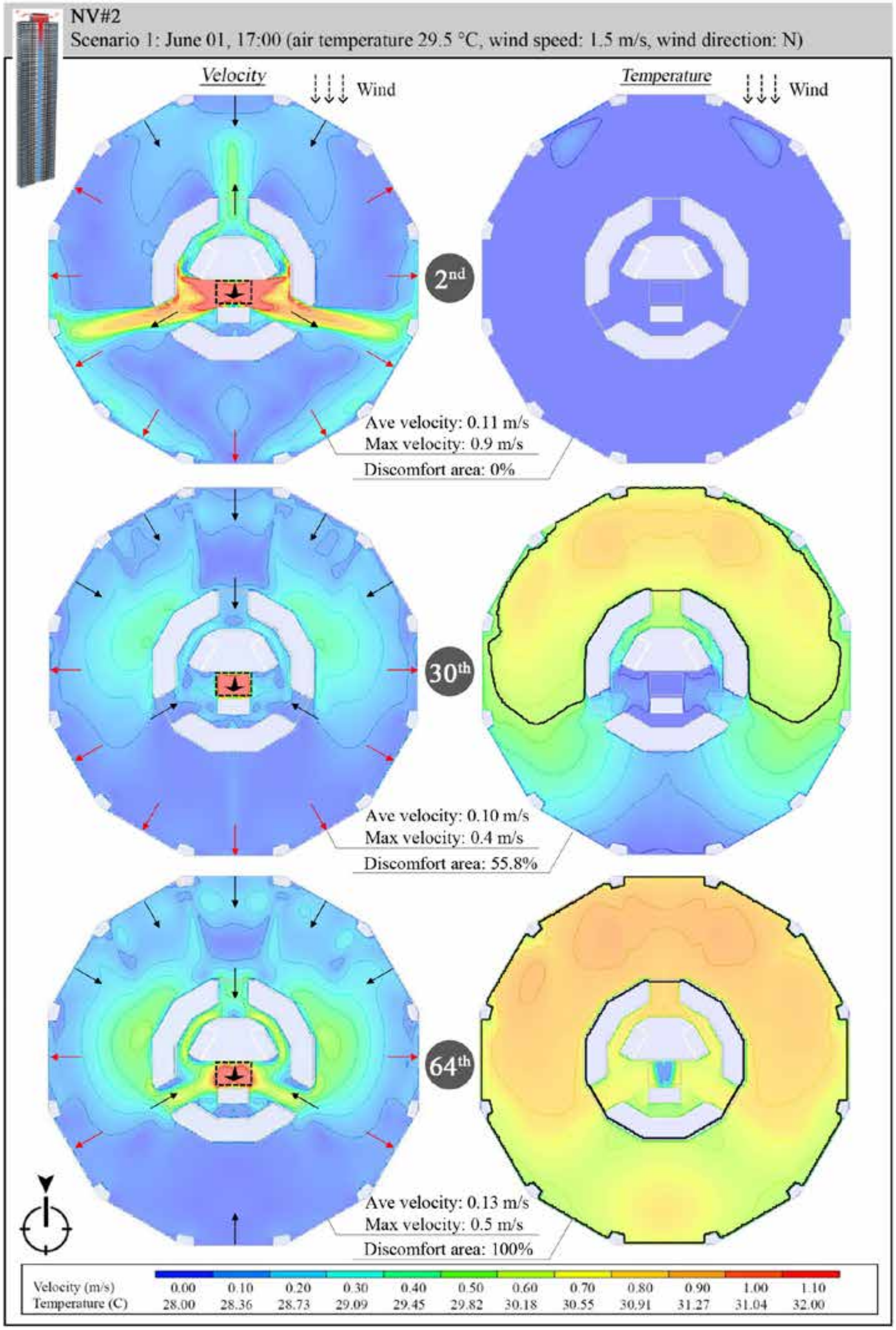
TOC

show that there is a certain degree of difference between the results from the two modelling tools (EnergyPlus and CFD). Generally, EnergyPlus and CFD provide a very different approach to the modelling of natural ventilation. In particular, horizontal and vertical stratification are not taken into account in most of the EnergyPlus airflow models. When using the EnergyPlus model, the average operative temperature of the entire office zone was used for the calculation of thermal comfort conditions on each test floor. However, by using the CFD model, air temperatures at the individual points throughout the working plane can be generated which let to measure the areas of comfort in a relatively more accurate way.

TOC

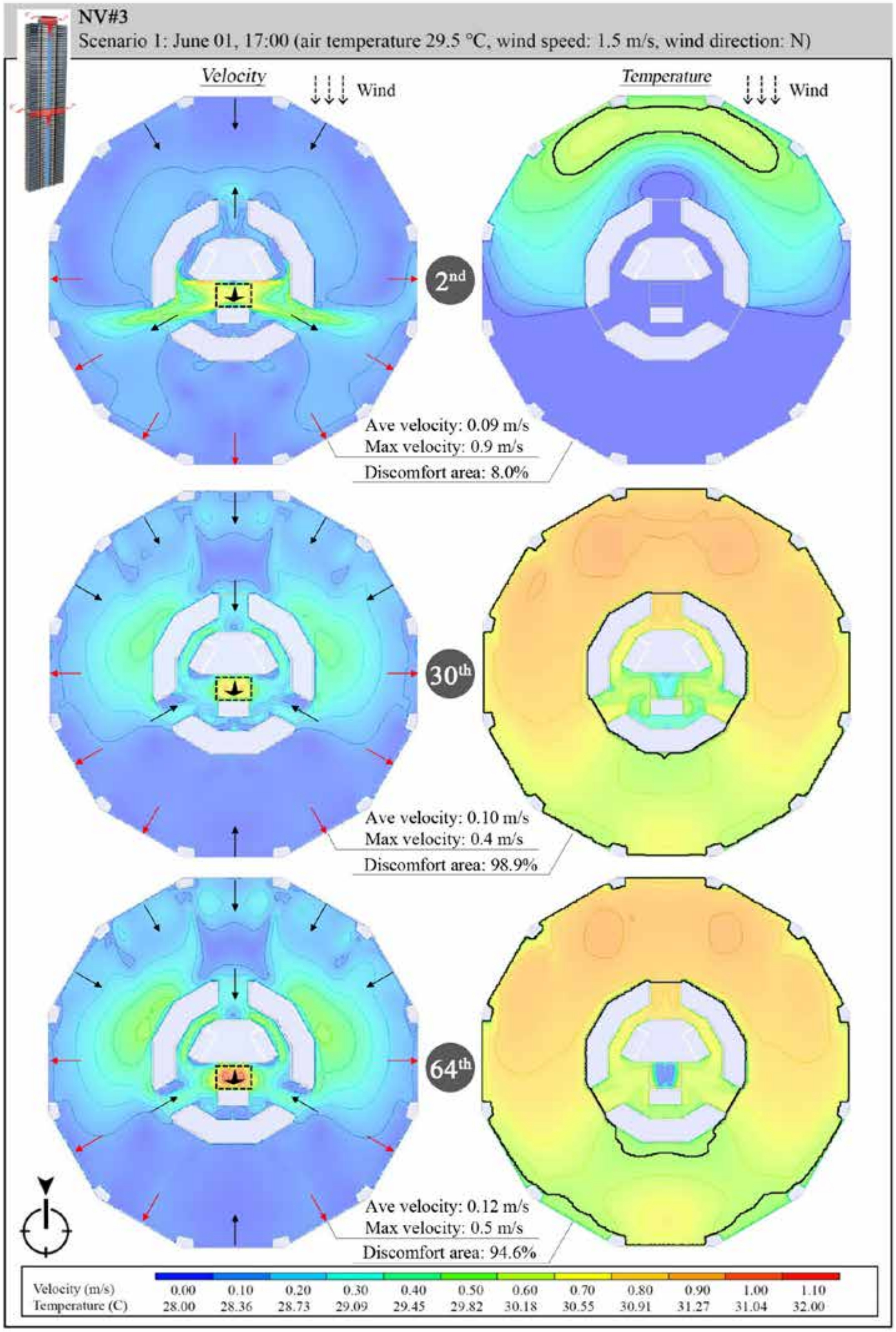

NV#1
Scenario 1: June 01, 17:00 (air temperature 29.5 °C, wind speed: 1.5 m/s, wind direction: N)
Velocity
Wind
Temperature
Wind
2nd
Ave velocity: 0.04 m/s
Max velocity: 0.1 m/s
Discomfort area: 52.3%
30th
Ave velocity: 0.12 m/s
Max velocity: 0.4 m/s
Discomfort area: 60.8%
64th
Ave velocity: 0.12 m/s
Max velocity: 0.5 m/s
Discomfort area: 58.2%
Velocity (m/s) 0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10
Temperature (C) 28.00 28.36 28.73 29.09 29.45 29.82 30.18 30.55 30.91 31.27 31.04 32.00

(a) NV#1


NV#2
Scenario 1: June 01, 17:00 (air temperature 29.5 °C, wind speed: 1.5 m/s, wind direction: N)
Velocity
Wind
Temperature
Wind
2nd
Ave velocity: 0.11 m/s
Max velocity: 0.9 m/s
Discomfort area: 0%
30th
Ave velocity: 0.10 m/s
Max velocity: 0.4 m/s
Discomfort area: 55.8%
64th
Ave velocity: 0.13 m/s
Max velocity: 0.5 m/s
Discomfort area: 100%
Velocity (m/s) 0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10
Temperature (C) 28.00 28.36 28.73 29.09 29.45 29.82 30.18 30.55 30.91 31.27 31.04 32.00

(b) NV#2

TOC


NV#3
Scenario 1: June 01, 17:00 (air temperature 29.5 °C, wind speed: 1.5 m/s, wind direction: N)
Velocity
Wind
Temperature
Wind
2nd
Ave velocity: 0.09 m/s
Max velocity: 0.9 m/s
Discomfort area: 8.0%
30th
Ave velocity: 0.10 m/s
Max velocity: 0.4 m/s
Discomfort area: 98.9%
64th
Ave velocity: 0.12 m/s
Max velocity: 0.5 m/s
Discomfort area: 94.6%
Velocity (m/s)
Temperature (C)
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10
28.00 28.36 28.73 29.09 29.45 29.82 30.18 30.55 30.91 31.27 31.04 32.00

(c) NV#3

TOC

FIGURE 5.23 The magnitude and direction of air flow and air temperature through the plan for different ventilation strategies under wind speed of 1.5 m/s and outside air temperature of 29.5 °C (June 01, 17:00). Under the temperature header, an enclosed area within the black line represents the discomfort area.

§ 5.9.2.2 Scenario 2 (no wind)

In scenario 2, the effectiveness of the buoyancy-induced versus the wind-induced ventilation was tested on a calm day with no wind. CFD simulations were carried out for an early morning hour (9:00) when the outdoor air temperature was around 29 °C. During the operation of the windows for natural ventilation (8:00-17:00), the outdoor air temperature is most likely to be most of the time higher than the indoor air temperature. The only time period when the outdoor air temperature is lower than the indoor air temperature is during early morning hours, usually between 8:00 to 10:00. The results show that when the indoor air temperature exceeds the outdoor temperature, an upward airflow will form in the vertical shaft in NV#2 and NV#3. This is caused by the formation of an under-pressure zone in the lower levels of the building, which pulls air inwards through the openings on the external façade. As the air moves through the building height it gains heat (by equipment and occupants) and creates an over-pressure zone at the top of the building. The differences in density between the indoor and outdoor air results in a different pressure gradient across the height of the building. The over-pressured areas at the top of the building drive air out of the openings, while the under-pressured areas at the base of the building pull air inwards through the openings. In case of NV#2 the height of the neutral pressure plane is at around 116 m above the ground, which is roughly halfway the height of the building.

In the absence of wind, cross ventilation will hardly occur (NV#1). Moreover, in order to achieve effective cross ventilation, the room depth should not exceed roughly five times its height (Wood & Salib, 2013). In case of the KOMTAR building this ratio is about three times higher than recommended. In NV#1, the average air velocity is equal to or less than 0.01 m/s on the three test floors. The results show that the application of the vertical shaft can increase the average velocities in a range between 0.04-0.12 m/s in NV#2, and 0.05-0.08 m/s in NV#3. This shows that the stack effect is the dominating driving force for natural ventilation in scenario 2. Furthermore, on a calm day stack ventilation is able to increase the indoor air velocity better than wind-driven ventilation.

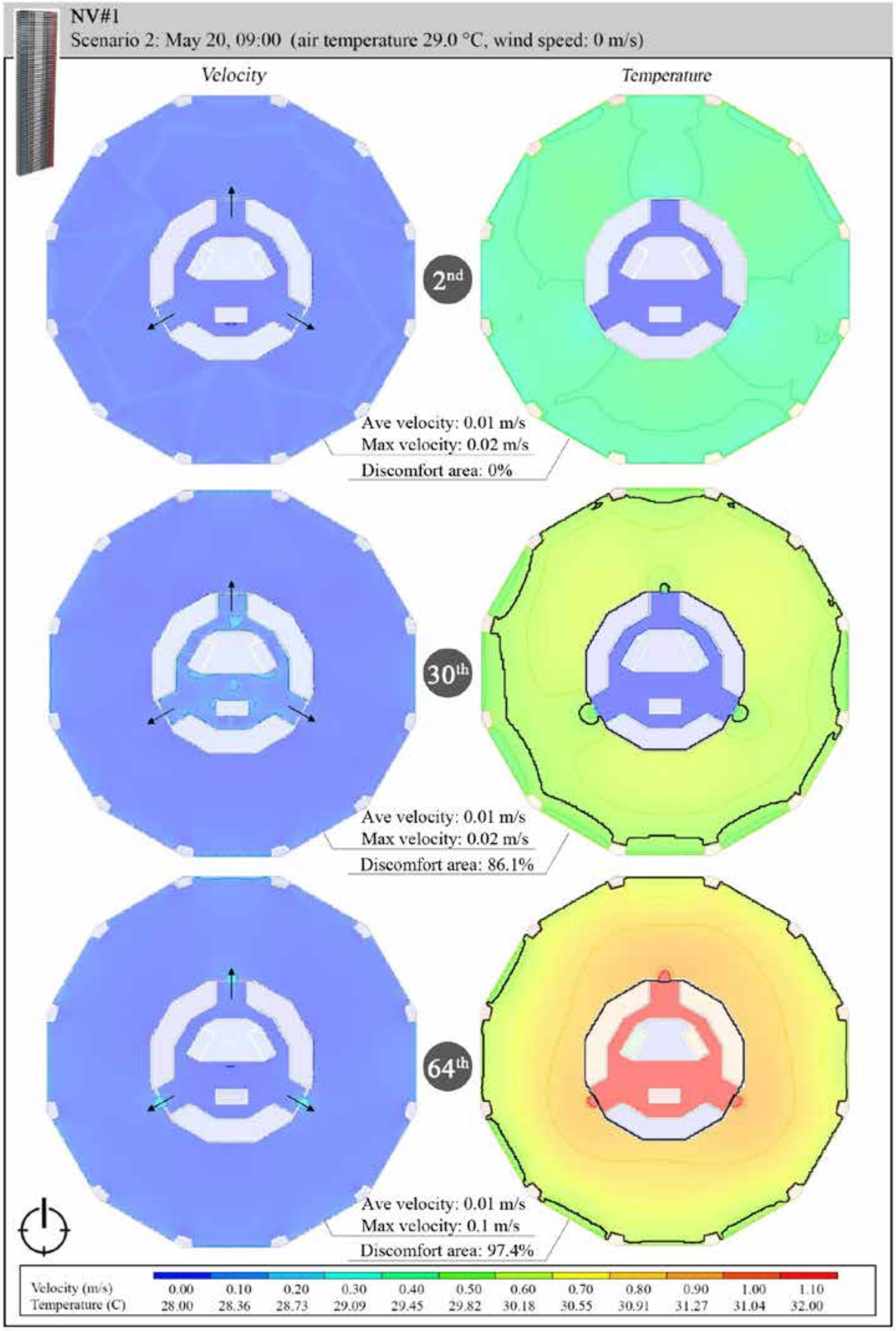
A full height atrium (NV#2) in comparison to a segmented atrium (NV#3), can make higher pressure differentials along the vertical shaft and therefore it can induce higher indoor air velocities on the base floor and the top floor. At mid-height (30th floor),

TOC

however, the average and maximum velocities are lower in NV#2 compared to NV#3. The reason is that this floor is located at a close distance from the neutral plane (32nd floor in case of NV#2), so that the indoor pressure and the outdoor pressure are almost equal to each other at this height in NV#2. Ventilation short circuits can be observed in the over-pressured areas on the upper levels such as the 64th floor in NV#2, or 30th and 64th floor in NV#3. Generally, air flows through the path of least resistance, so the areas of plan that are closer to the corridor openings exhibit higher air velocities. In this study, the effect of occupants and furniture layouts on air flow patterns are not taken into account for the office zones. Adjusting the layout of the furniture might be an effective solution to avoid short circuiting of natural ventilation.

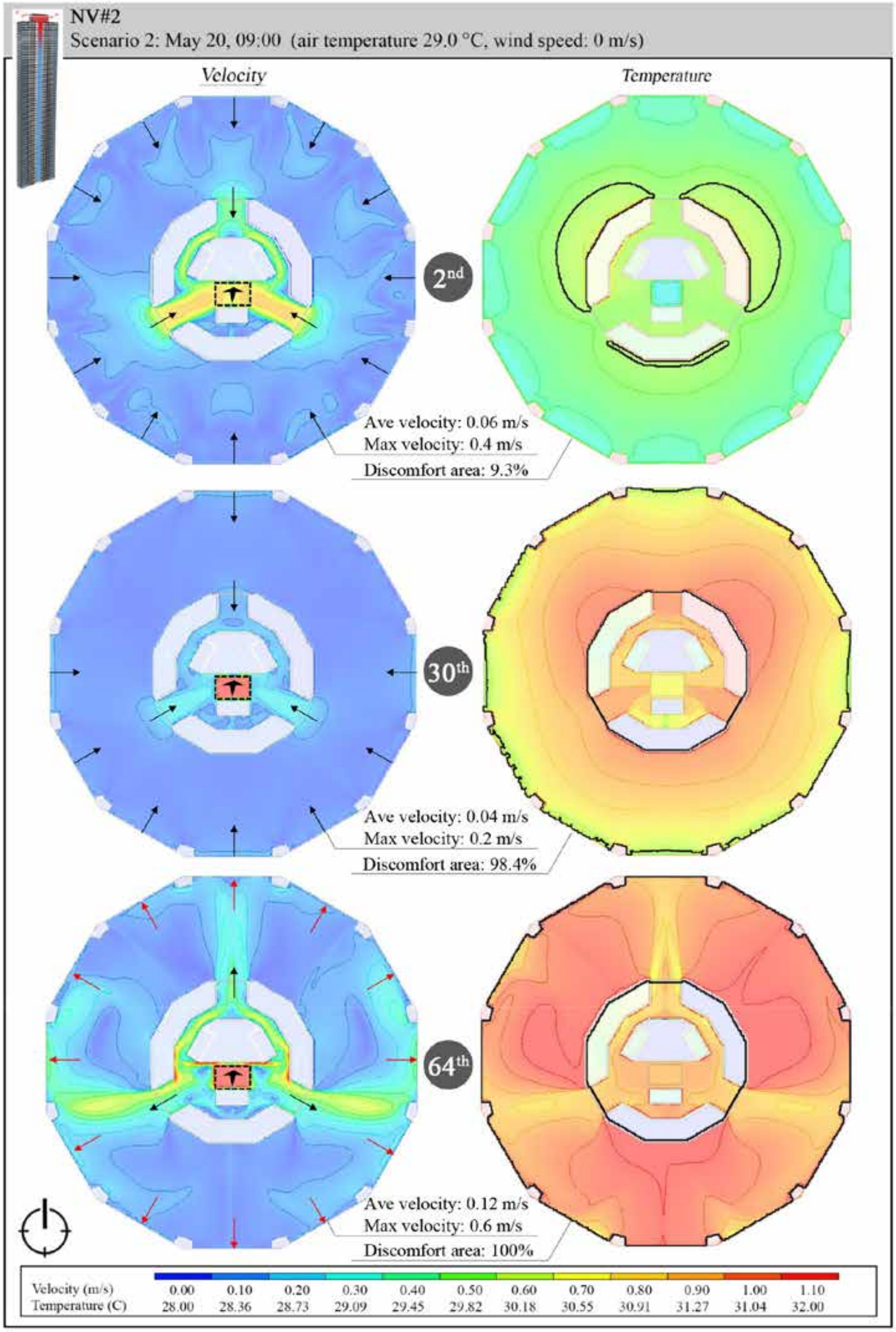
On the base level (2nd), the indoor air temperature is within the comfort boundaries for the majority of the office zone, while on the higher levels (30th and 64th), the indoor temperatures are beyond the upper limits of comfort temperature (30 °C) for almost the entire zone. During the morning hours, the cooler air flows inside the building through the openings on the lower floors and decreases the warmer indoor air temperature. The used (and warmed) air subsequently is being sucked out through the vertical shaft and exits the building from the openings on the upper floors, so that the upper levels would have a higher percentage of discomfort area. The results indicate that the average indoor air temperature for the three test floors in weather scenario 1 (June 01, 17:00) is relatively lower than the equivalent floors in scenario 2 (May 20, 09:00), despite a higher outdoor air temperature (0.5 °C) on June 1. In tropical climates, outdoor air temperatures are close to the upper comfort temperature range (or sometimes even higher). While lightweight constructions respond quickly to cooling breezes, heavyweight constructions delay the decrease of indoor air temperature. The heavyweight concrete structure of the KOMTAR building, besides the absence of wind, might be the reason for a higher percentage of thermal discomfort during the morning hours in scenario 2.

TOC

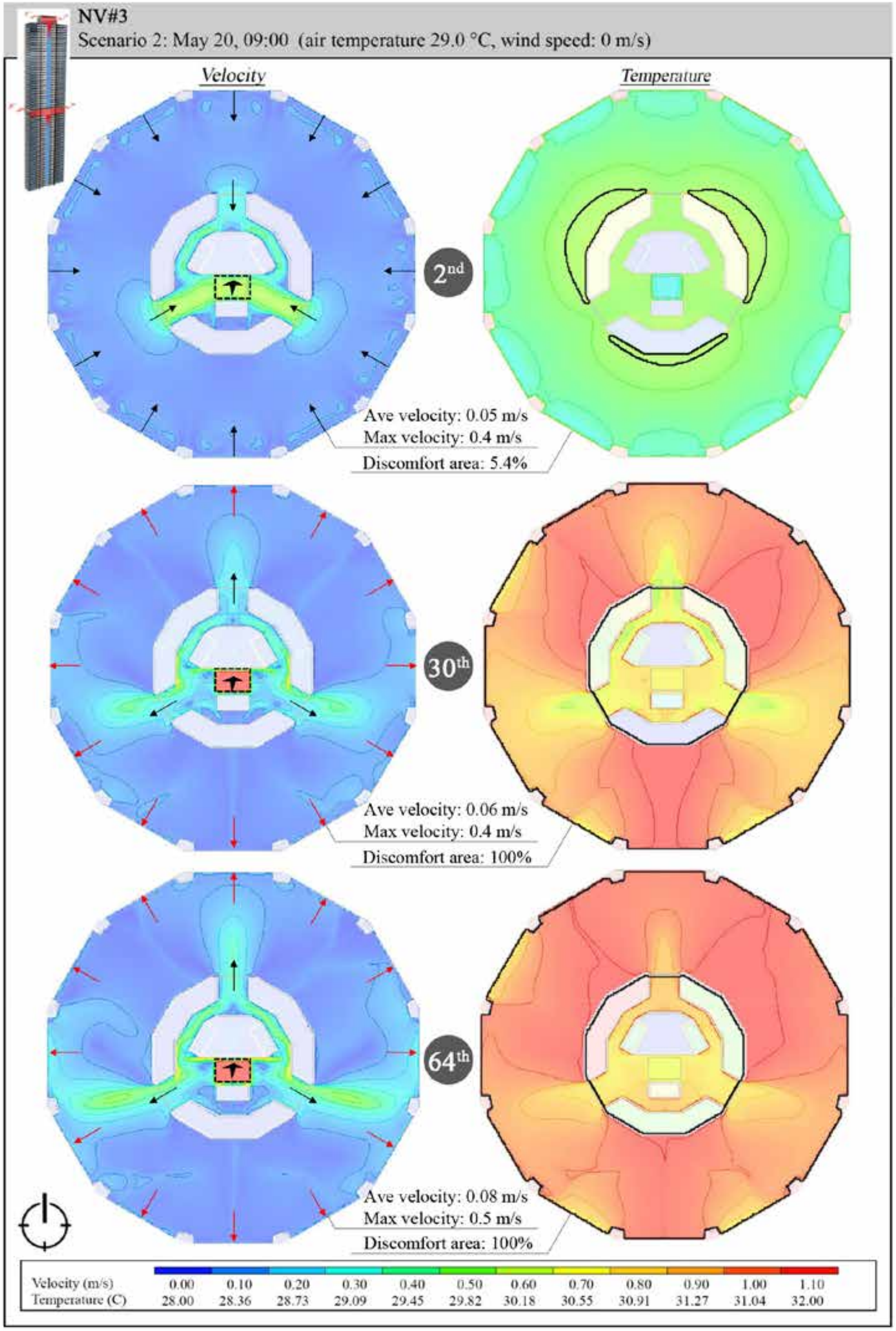

NV#1
Scenario 2: May 20, 09:00 (air temperature 29.0 °C, wind speed: 0 m/s)
Velocity
Temperature
2nd
Ave velocity: 0.01 m/s
Max velocity: 0.02 m/s
Discomfort area: 0%
30th
Ave velocity: 0.01 m/s
Max velocity: 0.02 m/s
Discomfort area: 86.1%
64th
Ave velocity: 0.01 m/s
Max velocity: 0.1 m/s
Discomfort area: 97.4%
Velocity (m/s) 0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10
Temperature (C) 28.00 28.36 28.73 29.09 29.45 29.82 30.18 30.55 30.91 31.27 31.04 32.00

(a) NV#1

TOC


NV#2
Scenario 2: May 20, 09:00 (air temperature 29.0 °C, wind speed: 0 m/s)
Velocity
Temperature
2nd
Ave velocity: 0.06 m/s
Max velocity: 0.4 m/s
Discomfort area: 9.3%
30th
Ave velocity: 0.04 m/s
Max velocity: 0.2 m/s
Discomfort area: 98.4%
64th
Ave velocity: 0.12 m/s
Max velocity: 0.6 m/s
Discomfort area: 100%
Velocity (m/s) 0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10
Temperature (C) 28.00 28.36 28.73 29.09 29.45 29.82 30.18 30.55 30.91 31.27 31.04 32.00

(b) NV#2


NV#3
Scenario 2: May 20, 09:00 (air temperature 29.0 °C, wind speed: 0 m/s)
Velocity
Temperature
2nd
Ave velocity: 0.05 m/s
Max velocity: 0.4 m/s
Discomfort area: 5.4%
30th
Ave velocity: 0.06 m/s
Max velocity: 0.4 m/s
Discomfort area: 100%
64th
Ave velocity: 0.08 m/s
Max velocity: 0.5 m/s
Discomfort area: 100%
Velocity (m/s)
Temperature (C)
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10
28.00 28.36 28.73 29.09 29.45 29.82 30.18 30.55 30.91 31.27 31.04 32.00

(c) NV#3

TOC

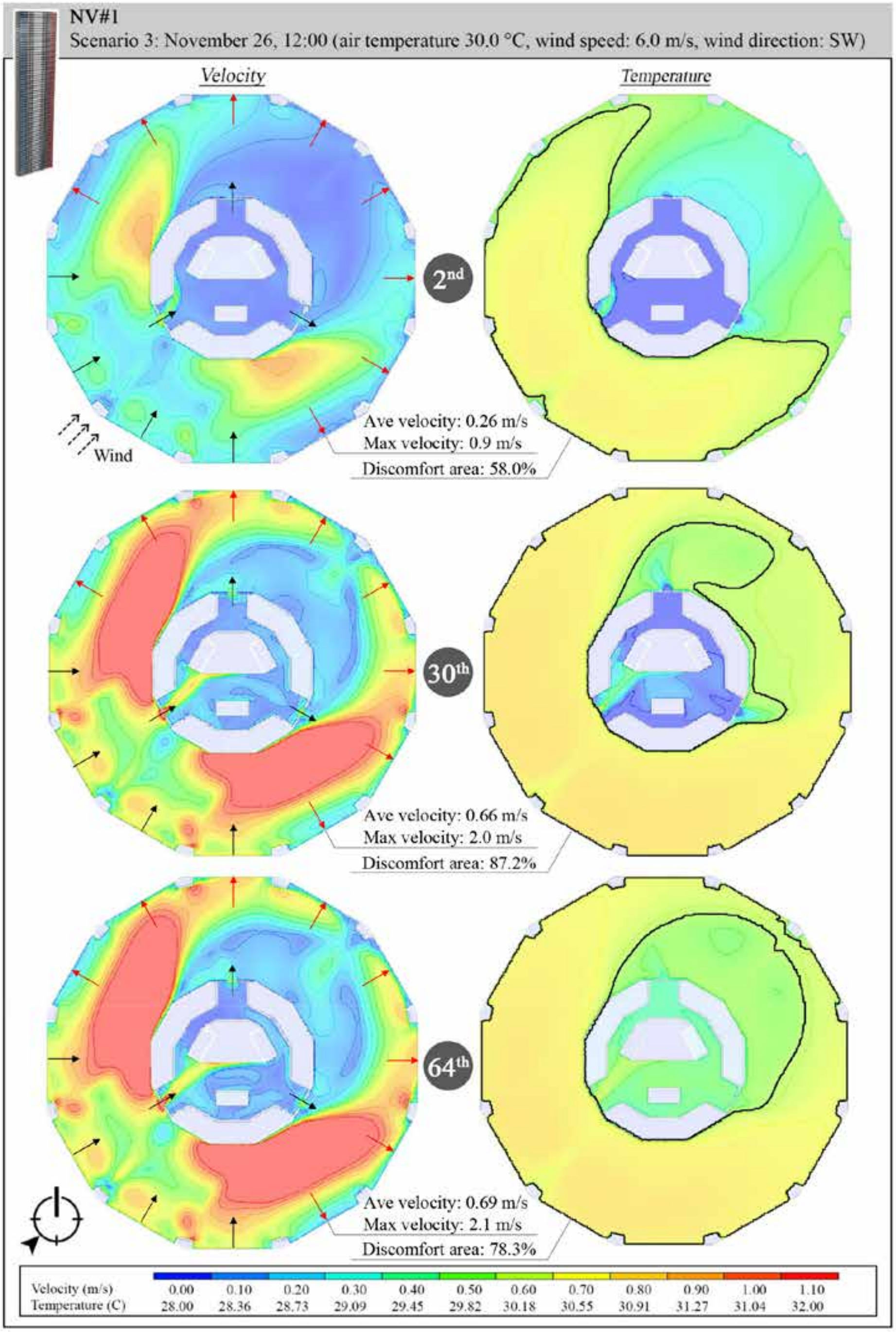
FIGURE 5.24 The magnitude and direction of air flow and air temperature through the plan for different ventilation strategies under wind speed of 0 m/s and outside air temperature of 29.0 °C (May 20, 09:00). Under the temperature header, an enclosed area within the black line represents the discomfort area.

§ 5.9.2.3 Scenario 3 (high wind speed)

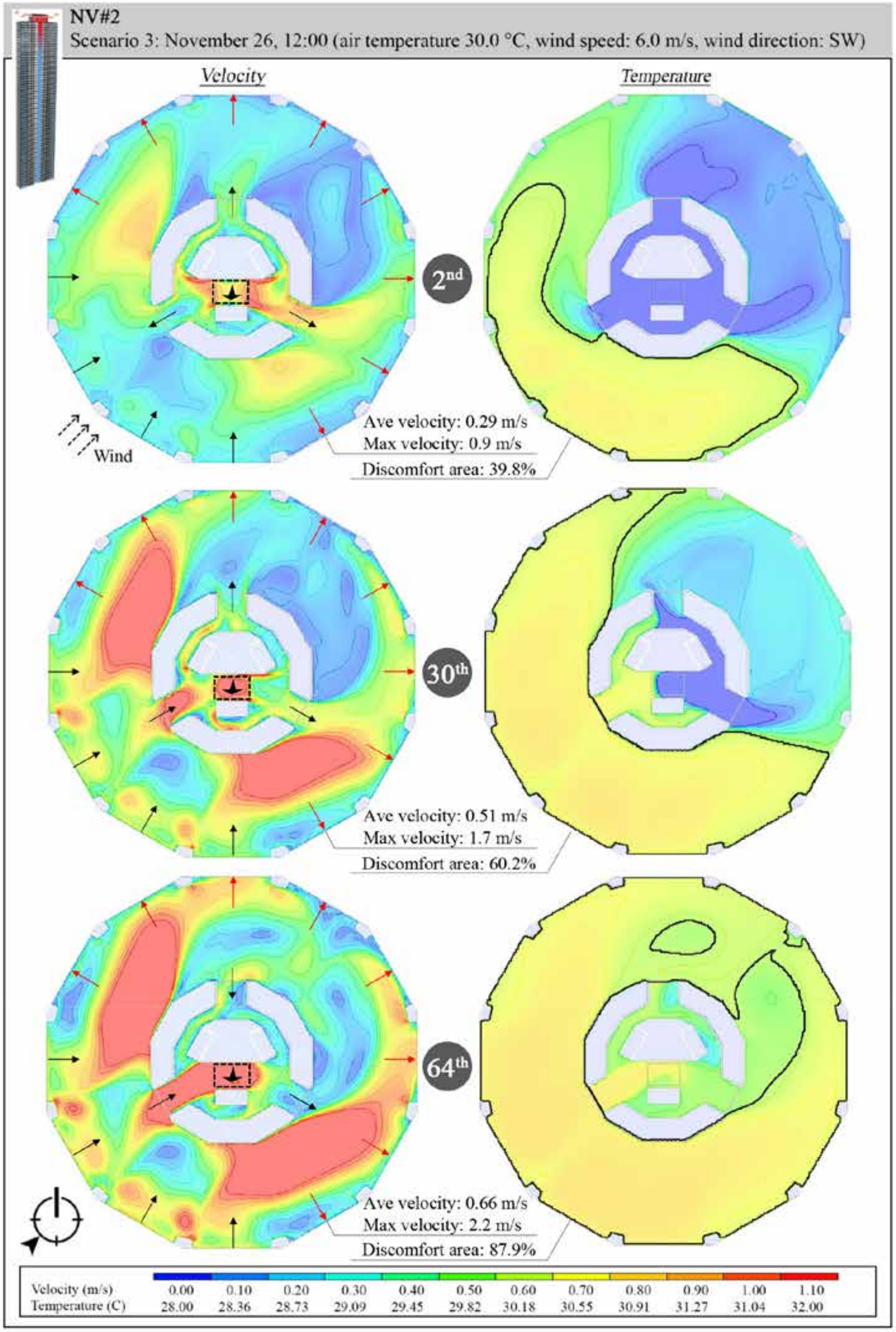
In scenario 3, the effectiveness of NV strategies was tested for extreme weather conditions when the wind speed is 6 m/s and it is coming from the south-west direction. Among all weather scenarios, the highest indoor air velocities are achieved in scenario 3. The average velocity reached a peak of 0.69 m/s in NV#1, while the maximum velocity reached a peak of 2.2 m/s in NV#2. The results show that the average and maximum velocities are significantly higher on the upper floor (64th) and the middle floor (30th) than on the base floor (2nd) for all NV strategies.

In NV#2, the air in the atrium moves down whereas in NV#3 it moves up. In NV#3, the indoor air temperature is warmer than the outdoor air temperature which would suggest an upward movement. Furthermore, the results show that the air flow through the vertical shaft in NV#2 and NV#3 is being disrupted by high winds passing through the corridor from the windward side. As a result, the buoyancy force plays a minor role in driving the natural ventilation and the pressure differentials generated by wind are the dominating driving force on a windy day. A comparison of the indoor velocity results between the three NV strategies shows that the average velocity and maximum velocity are both lower by about 0.15 m/s and 0.3 m/s in NV#2 and NV#3 as compared to NV#1. This means that buoyancy slightly counteracts cross ventilation here.

Since the outdoor air temperature is higher than the indoor air temperature, fresh air enters the building and a higher percentage of the office zone will be under the influence of high temperatures. For this reason, the mid-floor in NV#1 has the maximum discomfort area (87.2%) in comparison with the equivalent floors in NV#2 and NV#3. Furthermore, the minimum and maximum discomfort area belongs to NV#2; the lowest discomfort area is achieved for the 2nd floor (about 40%), while the highest discomfort area is achieved for the 64th floor (about 88%).

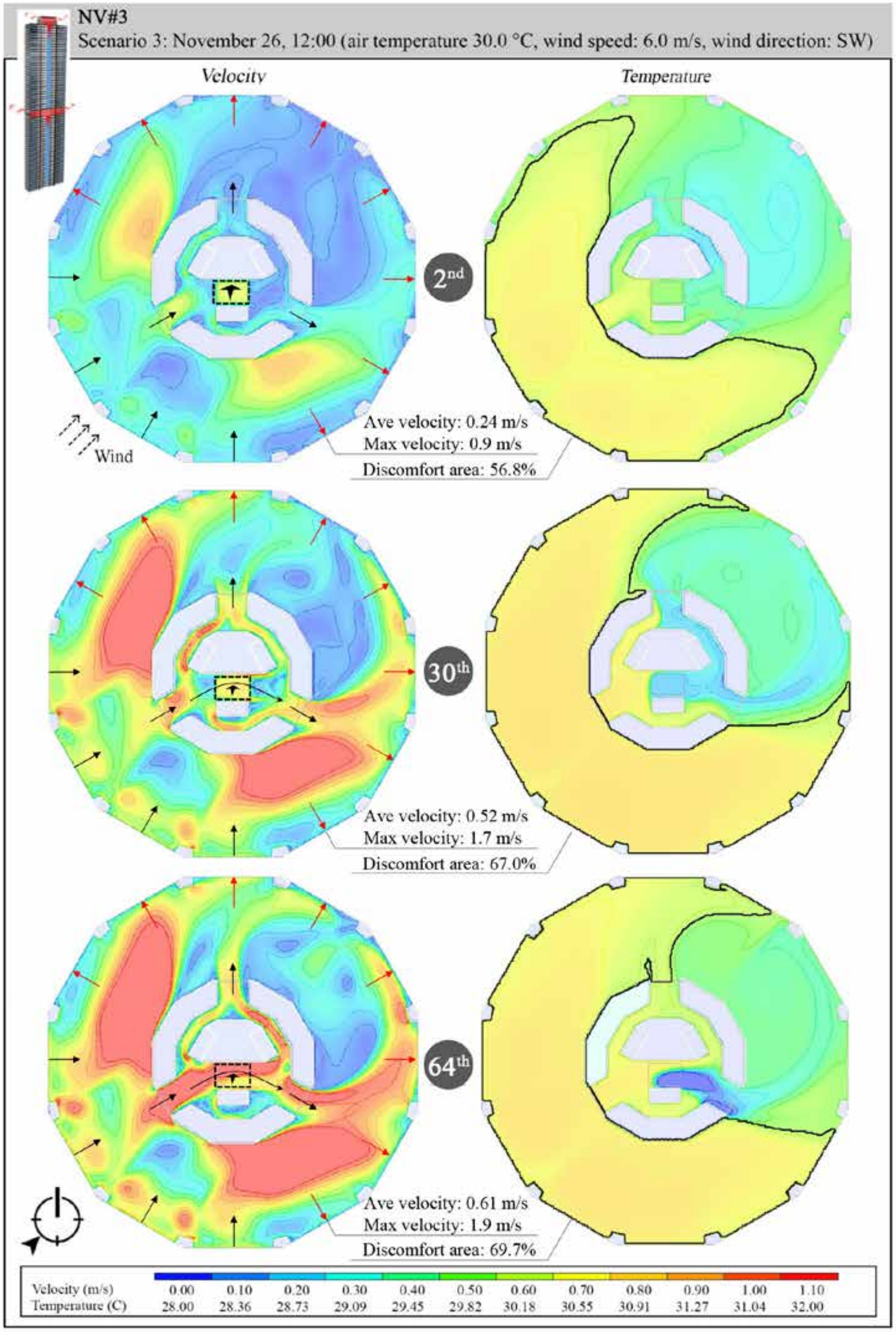

NV#1
Scenario 3: November 26, 12:00 (air temperature 30.0 °C, wind speed: 6.0 m/s, wind direction: SW)
Velocity
Temperature
2nd
Wind
Ave velocity: 0.26 m/s
Max velocity: 0.9 m/s
Discomfort area: 58.0%
30th
Ave velocity: 0.66 m/s
Max velocity: 2.0 m/s
Discomfort area: 87.2%
64th
Ave velocity: 0.69 m/s
Max velocity: 2.1 m/s
Discomfort area: 78.3%
Velocity (m/s)
Temperature (C)
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10
28.00 28.36 28.73 29.09 29.45 29.82 30.18 30.55 30.91 31.27 31.04 32.00

(a) NV#1


NV#2
Scenario 3: November 26, 12:00 (air temperature 30.0 °C, wind speed: 6.0 m/s, wind direction: SW)
Velocity
Temperature
2nd
Ave velocity: 0.29 m/s
Max velocity: 0.9 m/s
Discomfort area: 39.8%
Wind
30th
Ave velocity: 0.51 m/s
Max velocity: 1.7 m/s
Discomfort area: 60.2%
64th
Ave velocity: 0.66 m/s
Max velocity: 2.2 m/s
Discomfort area: 87.9%
Velocity (m/s) 0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10
Temperature (C) 28.00 28.36 28.73 29.09 29.45 29.82 30.18 30.55 30.91 31.27 31.04 32.00

(b) NV#2

TOC


NV#3
Scenario 3: November 26, 12:00 (air temperature 30.0 °C, wind speed: 6.0 m/s, wind direction: SW)
Velocity
Temperature
2nd
Wind
Ave velocity: 0.24 m/s
Max velocity: 0.9 m/s
Discomfort area: 56.8%
30th
Ave velocity: 0.52 m/s
Max velocity: 1.7 m/s
Discomfort area: 67.0%
64th
Ave velocity: 0.61 m/s
Max velocity: 1.9 m/s
Discomfort area: 69.7%
Velocity (m/s)
Temperature (C)
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10
28.00 28.36 28.73 29.09 29.45 29.82 30.18 30.55 30.91 31.27 31.04 32.00

(c) NV#3

FIGURE 5.25 The magnitude and direction of air flow and air temperature through the plan for different ventilation strategies under wind speed of 6 m/s and outside air temperature of 30.0 °C (November 26, 12:00). Under the temperature header, an enclosed area within the black line represents the discomfort area.

§ 5.9.3 Cooling effect of elevated velocities

The physiological cooling effect of air movement through enhanced evaporation from the human skin is one of the most important passive control techniques in hot and humid climates. In order to calculate the potential cooling effect of elevated velocities, Szokolay's physiological cooling equation (Auliciems & Szokolay, 2007) is implemented.

$$\Delta T = 6\times(v-0.2) - 1.6\times(v-0.2)^2$$

Where ΔT (K) is the cooling effect by elevated air velocity, and v (m/s) is the air velocity at the body surface. This equation gives a numerical approximation of this cooling effect for velocities between 0.2 and 2 m/s. In Figure 5.26, the potential cooling effect of various velocities between 0.2-2 m/s is plotted by using Szokolay's equation. There is no cooling effect for velocities below 0.2 m/s. An increase of indoor air velocity till 2.0 m/s could extend the upper comfort limit by as much as 5.6 K. It is important to note that air velocities beyond 1.5 m/s can cause light objects such as papers to be blown away in the office area and therefore, it may override any desirable cooling effect (Szokolay, 1997). In this study, the maximum cooling effect of NV strategies to reduce thermal discomfort is calculated by taking velocities of up to 2 m/s.

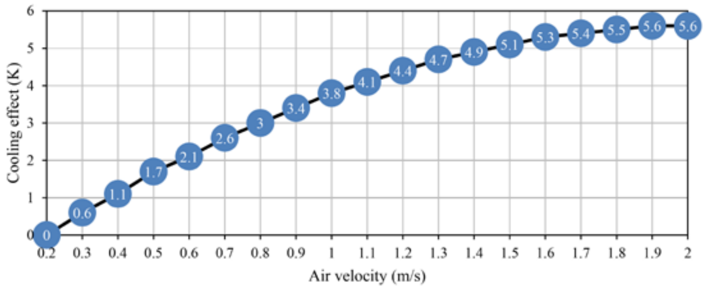


FIGURE 5.26 Cooling effect of elevated air velocity based on the physiological cooling model of Szokolay.

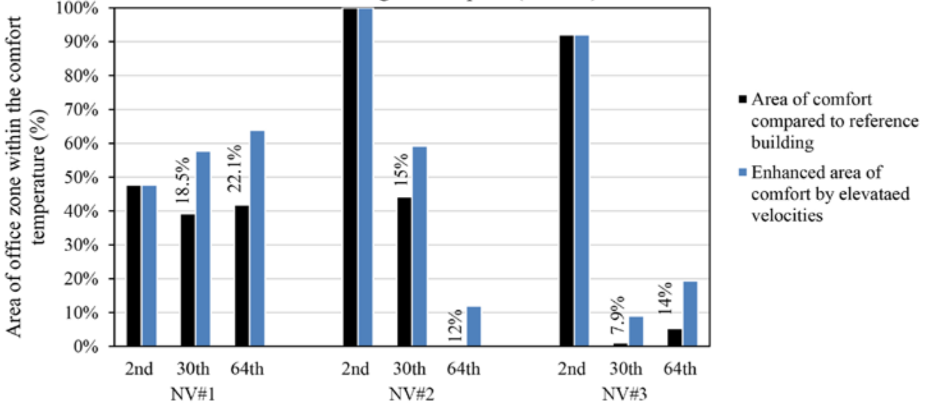
TOC

By using the results of Figure 5.26, the increased comfort area in the office zone on the three test floors due to elevated velocities is calculated for all ventilation strategies. The results are presented in Figure 5.27 (a, b, and c) for different weather scenarios. Additionally, in appendix 1 (a, b, and c), the graphical maps on the working planes show the exact locations of discomfort areas for the different NV strategies prior and after taking the physiological cooling effect of elevated velocities into account. The cooling potential of elevated velocities would be very limited when taking the wider comfort temperature range (±3 K). For this reason, for the calculation of the discomfort area, the narrower comfort temperature range (±2 K) was chosen. In case of the reference design with an air-conditioning system, the area of discomfort was calculated on different test floors for when the system is shut off. The indoor air temperatures for the entire office zone at different floors were higher than the adjusted cooling set point temperature (24 °C) under different weather scenarios.

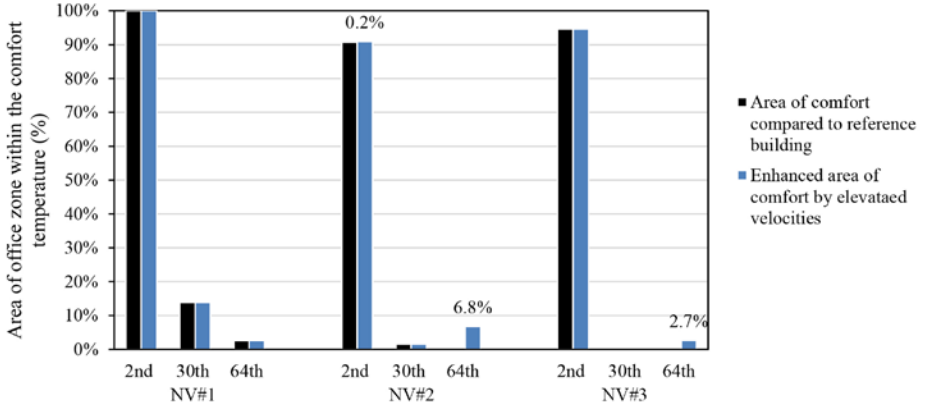
In scenario 1 (Figure 5.27a), the increased area of comfort due to the cooling effect of elevated velocities is in a range between 7.9% and 22.1% depending on the effectiveness of a NV strategy for increasing the air flow on a particular floor. A wind-driven ventilation strategy (NV#1) is able to improve the comfort area on different test floors almost in the same range. The range of comfort area is increased from 39%-48% to 48%-64% when adding the cooling effect of elevated velocities. In case of the buoyancy-driven ventilation, the percentage of comfort area has a direct relationship with the location of the test floors alongside the vertical shaft. The base floor has the largest comfort zone amongst the test floors by around 100% of the floor area in NV#2 and 92% in NV#3. for the higher floors, the area of comfort reduces. The area of comfort is between 10%-20% for those three top floors that are located at close distance from the air outlets of the vertical shaft; 30th and 64th in NV#3 and 64th in NV#2.

In scenario 2 (Figure 5.27b), in the absence of wind, the indoor air velocity is very low. Higher velocities that can provide a cooling effect (higher than 0.2 m/s) only exist in over-pressured areas at the upper-levels of the building in NV#2 and NV#3. Due to ventilation short circuits in over-pressured areas, a small percentage of floor space can take the advantage of higher velocities. The increased comfort area is therefore about 6.8% in NV#2, and 2.7% in NV#3 for the upper floors. When there is no wind, the area of the office zone that has an indoor air temperature within the upper comfort limit of 30 °C is up to 14%, with the exception of lower-levels that have a higher comfort area. On the base floor, between 90%-100% of the total office area has an indoor temperature within the comfort boundaries.

(a) Scenario 1: average wind speed (1.5 m/s)



Scenario 2: no wind



(c) Scenario 3: high wind speed (6.0 m/s)

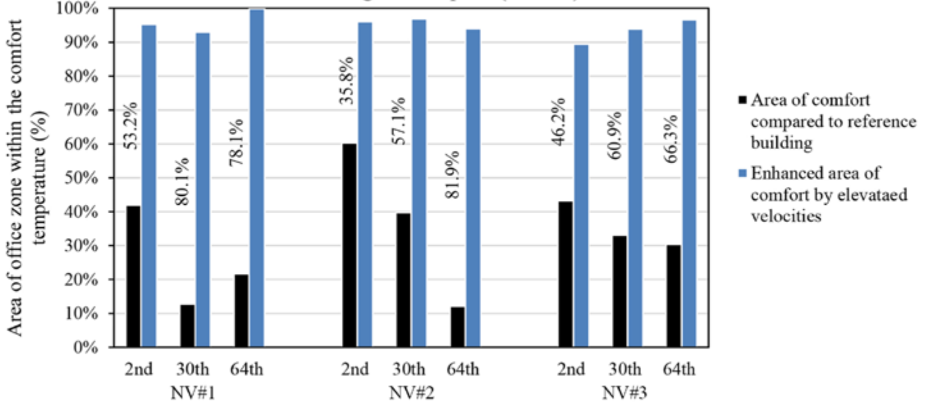


FIGURE 5.27 The increased area of comfort by the application of NV strategies and the enhanced cooling effect due to elevated velocities under three weather scenarios.

In scenario 3 (Figure 5.27c), the range of comfort area is increased from 12%-60% to 89%-100% when adding the cooling effect of elevated velocities by the application of NV strategies. This indicates the importance of elevated velocities for improving thermal comfort conditions in hot and humid climates. However, it should be noted that this high range of comfort is only possible during the rare periods of high wind speed.

§ 5.10 Conclusion

In this chapter the potential use of natural ventilation strategies to reduce the energy demand for cooling and mechanical ventilation was investigated. The KOMTAR tower was selected as a conventional design for tall office buildings in the tropical climate. Three natural ventilation strategies were developed, and EnergyPlus combined with the CFD code in DesignBuilder, was employed for the purpose of investigation. It was found that on average between 96.8%-99.8% of the occupancy hours, natural ventilation strategies can meet the minimum fresh air requirements needed for an office space. However, an assistant mechanical ventilation system might be essential for up to 10% of the occupancy time on certain floors depending on the physical mechanism driving the air flow. Those floors that are in higher demand for mechanical ventilation are the lower floors of a building with a wind-induced ventilation strategy, and the middle floors of a building with a buoyancy-induced ventilation strategy.

Furthermore, the results showed that the application of natural ventilation strategies can considerably reduce the percentage of the occupancy time when air-conditioning is required for space cooling in the reference building: between 80%-88% for the wider comfort boundaries and between 56%-65% for when selecting the narrower comfort boundaries. The following natural ventilation strategies have the highest to lowest number of comfort hours: buoyancy-driven ventilation using a full height atrium (NV#2), buoyancy-driven ventilation using a segmented atrium (NV#3), and wind-driven ventilation (NV#1). However, in practice the demand for mechanical ventilation and cooling can increase to a higher level when considering the influence of other factors such as surrounding buildings, undesirable outdoor conditions (noise, air pollution, high humidity and wind speed) and occupant behaviour on the operation of natural ventilation.

In the next step, CFD simulations were employed to investigate the potential use of ventilation alternatives to extend thermal comfort by using Szokolay's physiological cooling equation. With the application of NV strategies, the average percentage (at different floors under different weather scenarios) of comfort area (based on 90% acceptability limits) increased to 25% in NV#1, 39% in NV#2, and 33% in NV#3. The area of comfort can be extended further when adding the physiological cooling effect of elevated velocities. The results showed that the increased area of comfort due to elevated velocities were 53% in NV#1, 62% in NV#2, and 55% in NV#3.

In this study, the performance of three test floors connected to a ventilation shaft was tested for the situation that the shaft is connected to only three floors. The indoor velocity and temperature might therefore be slightly different from the situation in which the vertical shaft is connected to a large number of floors along the building height. Additionally, for the study of a segmented vertical shaft, the middle floor (30th) might not be a good representative of a mid-level floor for the purpose of comparison with the other two strategies as it is located at close proximity to the air outlets on the wind floor. However, for the reason of keeping the outdoor conditions (e.g. temperature and wind) the same among NV strategies, the location of the proposed test floors was kept unchanged. So, the average comfort level of the three test floors in NV#3 might be underestimated due to a lower performance of the 30th floor.

In tropical climates, wind speeds are low, stack effects are small and outdoor air temperatures are close to the upper comfort temperature limits. All these factors make the implementation of natural ventilation strategies more challenging in this climate. Increasing the indoor velocity is essential for achieving thermal comfort conditions in such a climate. Greater velocities could extend the upper comfort limit by up to 5.6 K due to enhanced evaporation from the human skin. The design of tall buildings (external envelope and internal layout) should be able to facilitate the air flow across the interior spaces. In this regard, curved or funnel-shaped structures can be used to lead the wind in desired directions. Another effective strategy to capture wind from a wide range of directions is through the outward extension of walls (wind wing walls) when site limitations do not allow to orient the building along the prevailing wind axes. Finally, a natural ventilation strategy that employs wind and buoyancy driving forces together can provide greater chances of having higher indoor velocities under different wind conditions.

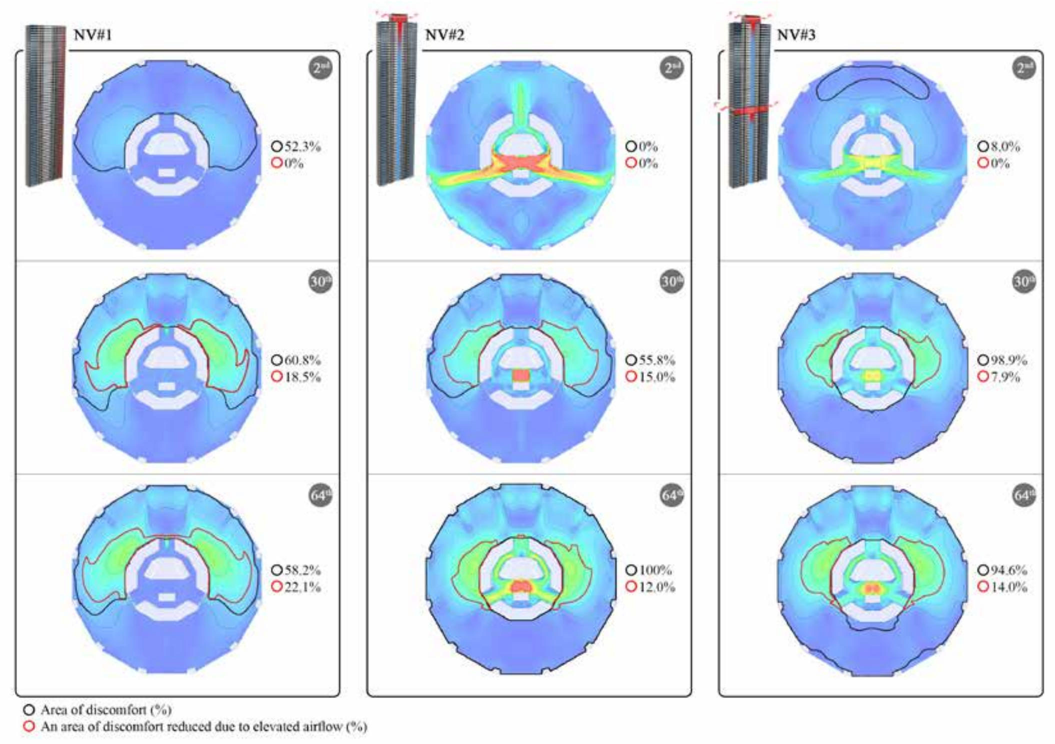


FIGURE 5.28 A comparison of discomfort area for different NV strategies prior and after taking the psychological cooling effect of elevated velocities into account in weather scenario 1: June 01, 17:00 (air temperature 29.5 °C, wind speed 1.5 m/s, wind direction: N).

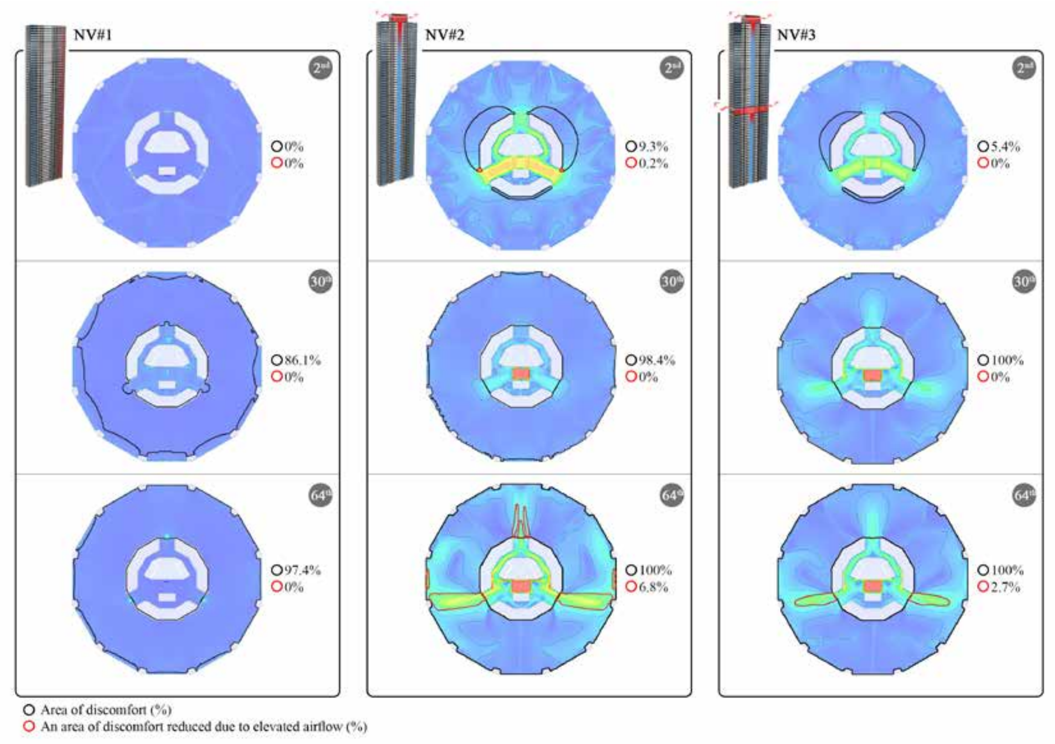


FIGURE 5.29 A comparison of discomfort area for different NV strategies prior and after taking the psychological cooling effect of elevated velocities into account in weather scenario 2: May 01, 09:00 (air temperature 29.0 °C, no wind speed).

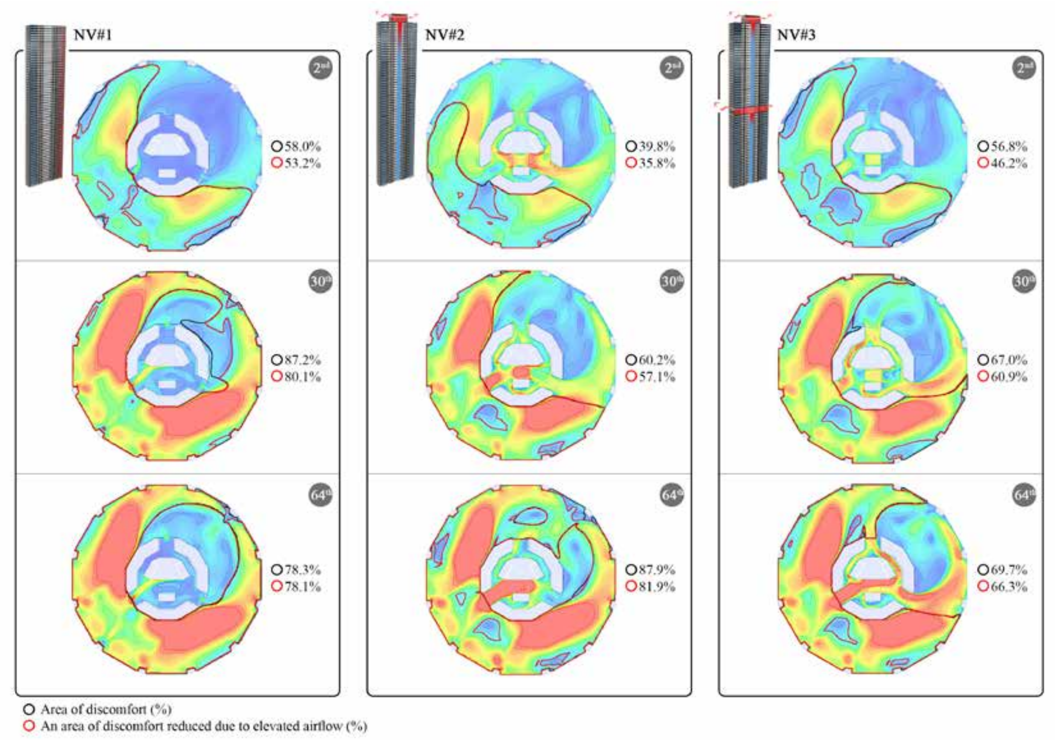


FIGURE 5.30 A comparison of discomfort area for different NV strategies prior and after taking the psychological cooling effect of elevated velocities into account in weather scenario 3: November 26, 12:00 (air temperature 30.0 °C, wind speed 6.0 m/s, wind direction SW).

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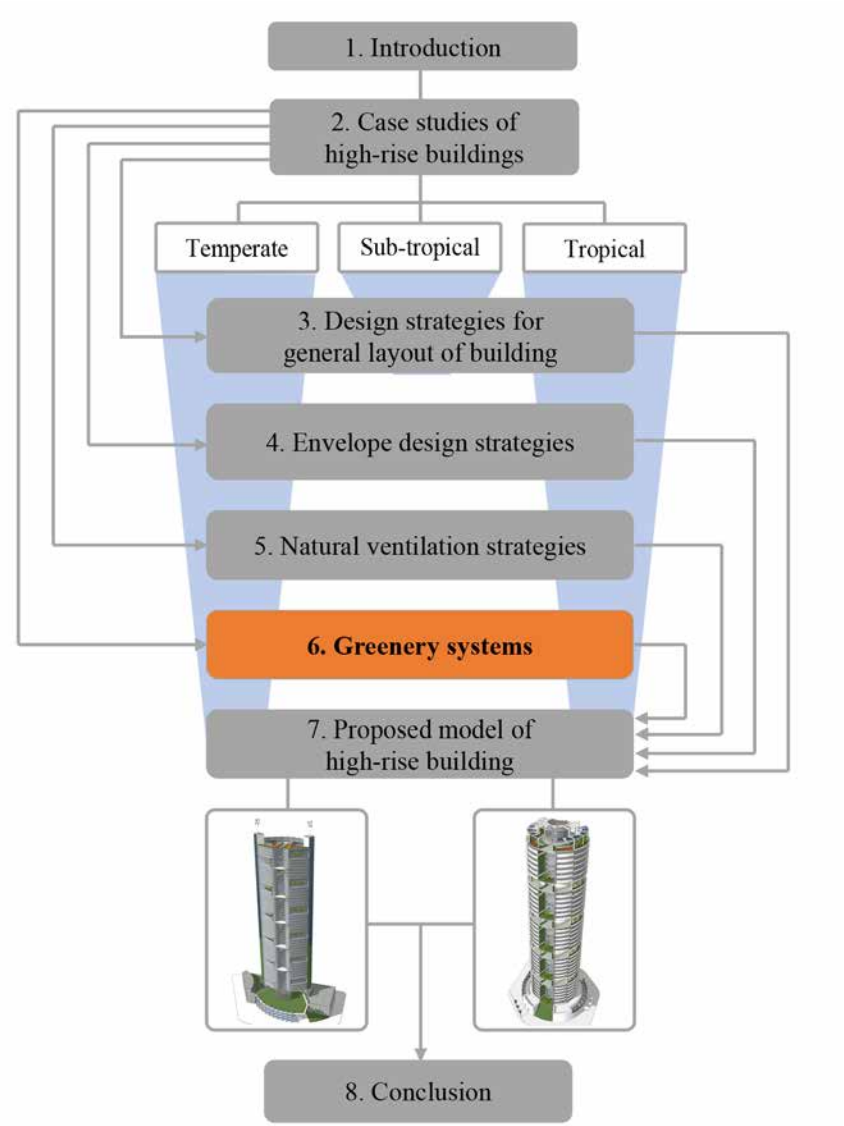
1. Introduction
2. Case studies of high-rise buildings
Temperate
Sub-tropical
Tropical
3. Design strategies for general layout of building
4. Envelope design strategies
5. Natural ventilation strategies
6. Greenery systems
7. Proposed model of high-rise building
8. Conclusion

6 Greenery systems

In the previous chapters, the impact of geometric factors, envelope strategies and natural ventilation solutions for improving the energy performance and thermal comfort of tall office buildings was assessed through running a large number of energy and CFD simulations. The results of the previous chapter showed that for a naturally ventilated tall office building on average only 4% of the occupancy hours a supplementary air-conditioning system might be needed for providing thermal comfort during summer in the temperate climate. For the tropical climate, the average percentage of discomfort hours (when air-conditioning is required to keep the indoor air temperature within the comfort limits) was around 16% of the occupancy hours during one year.

The last important strategy that is becoming an integrated part of sustainable tall buildings is the use of greenery systems. Chapter 6 provides an in-depth literature review for different greening systems including green roofs, vertical greening, green balconies, sky gardens, and indoor sky gardens. Each greenery system will be investigated for its impact on temperature, heat flux and HVAC systems. For indoor plants their influence on indoor air quality and users' perception will also be discussed. In section 6.4 the impact of greenery concepts will be concluded in terms of comfort, energy and suitability for different climates.

The impact of greening systems on building energy performance: A literature review[5]

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Abstract

Scarcity of resources and environmental issues caused by human activities stimulate designers and policy makers to search for energy efficient strategies for sustainable development. A considerable amount of energy consumption and CO_2 *emission comes from the building sector which today accounts for 40% of the world's energy use. Greenery systems are considered as a promising solution for making buildings more energy efficient. However, energy saving is one among multiple benefits that a greenery system can offer to a building. The most common places in a building that can be used to accommodate vegetation include roof greening, vertical greening, terrace planting and sky gardens (indoor and outdoor) especially in the design of high-rises. Therefore, the main aim of this paper is to provide a literature review for all different greening systems with respect to their energy impact. The role of indoor planting on thermal comfort and indoor air quality (IAQ) will also be discussed. Furthermore, the suitability of different greenery systems for different climate types is summarized.*

Keywords

Greening systems, energy saving, indoor air quality, evapotranspiration, shading, thermal insulation.

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§ 6.1 Introduction

For the first time in 2008, over half of the world population lived in cities. The United Nations estimates that by 2050, the urban population will reach a new peak of around 67% [1]. According to Wood [2], with the current rate of urbanization, a new city is needed to accommodate one million new urban inhabitants around the world every week. A big challenge for urban planners in the 21st century is accommodating these new urban inhabitants with adequate facilities.

Dense urban areas have been the source of environmental issues like urban heat island, depletion of resources and air and water pollutions. Therefore, designers and planners should take sustainability in the development of buildings into account. It means that in the future designs of our built environment should be climate-adaptive and rely on renewable and recyclable resources [3]. To adapt our built environment to the natural environment, Yeang suggests that "our constructions must imitate ecosystems in all aspects" (p. 412) [4].

Typically, dense urban areas are composed of a huge quantity of inorganic resources from distant places and assembled intensively in a small portion of land; therefore, they exert a dramatic pressure on the biosphere by changing the balance of organic and inorganic content. According to Yeang we must maintain a balance between biotic and abiotic through adding appropriate levels of biomass, improving biodiversity and making ecological connections in our built environment [4]. In line with Yeang, Wood [2] noted that if cities are seeking to accommodate a large group of people on the same area by building upward, then they require imitating the ground floor atmosphere up in the sky, including green spaces, sidewalks and other public functions.

The most common places in a building that can be used to accommodate vegetation are roof greening, vertical greening, terrace planting and using indoor plants in atria especially in the design of high-rises, as shown in Figure 6.1. In recent years, much research has been done on the benefits of using greenery concepts with different objectives, scopes and methodologies. However, there has been more research done in some areas than in others. The main aim of this paper is to provide a literature review for all different greening systems with respect to energy impact.

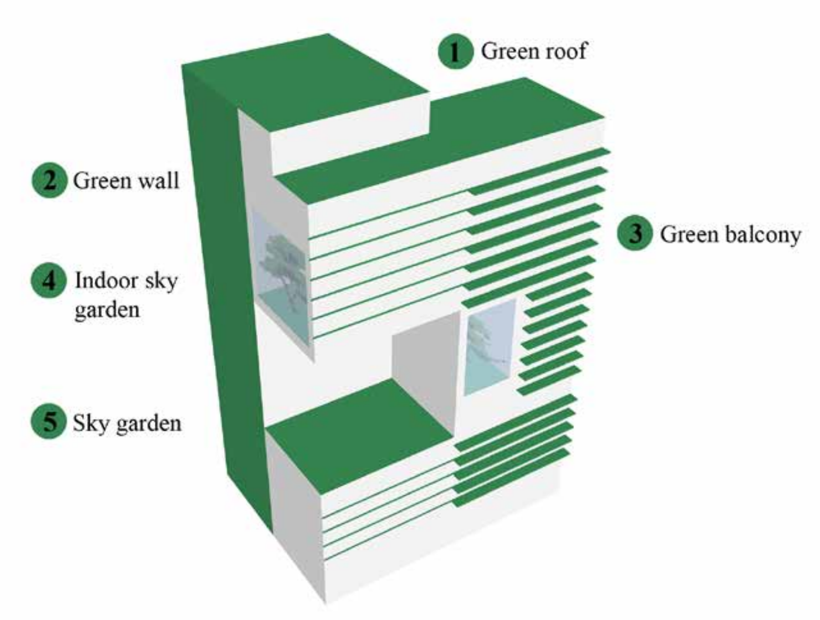

FIGURE 6.1 Different ways of integrating greenery systems on buildings.

§ 6.2 Methods

This paper presents literature concerning the application of greenery systems on our built environment, with a focus on energy related topics. The literature review looks at a time frame from 1977 through late 2013 and encompasses five greenery concepts including the green roof (GR), green wall (GW), green balcony (GB), sky garden (SG) and indoor sky garden (ISG). Each greenery concept is investigated in a separate section. Therefore, each section includes an overview on the history, definitions and different categories of that greenery concept followed by its potential benefits for a building. After a brief introduction, the thermal impact of each concept, besides its impact on building's energy consumption, will be studied. As there has been little research available on some areas like green balconies or sky gardens, the aim is to fill these gaps through reviewing the studies that might provide the same benefits of shading trees nearby buildings. Furthermore, for indoor greenery concepts, their effect on building indoor air quality will also be studied.

TOC

Therefore, the literature review was undertaken with the objectives of:

- Studying the possible greenery concepts for building designs.
- Determining the impact of different variables in each greenery system which influence the temperature and heat flux
- Determining the energy impacts of greenery systems on HVAC systems
- In order to avoid a long list of references in the text, they were split into major and minor references. The major works are the critical sources that are used in the analysis and therefore are cited in the text. The minor works are not numbered but are used to draw the conclusions; thus, presented in the appendix 1.

§ 6.3 Greenery concepts

§ 6.3.1 Green roofs

§ 6.3.1.1 Introduction

Roofs allocate approximately 20-25% of the total urban surface [5]; therefore, greening them can have a significant influence at the building scale and at the city scale. The green roof is the most common greenery concept, mostly in use in European, North-American and also some tropical Asian countries. Germany is considered the world pioneer in developing green roof technologies [6]. A green roof is a combination of different supportive layers that provide conditions for growing vegetation on a flat or sloped rooftop. A green roof's layer from top to bottom include the vegetation layer, growing medium, filter, drainage (moisture retention), root barrier and finally waterproofing membrane on top of a structural deck [7].

In accordance with the type of usage, construction factors and maintenance requirements, green roofs are typically divided into three major groups: extensive, intensive and semi-intensive roofs. The extensive type has a relatively thin layer of growing medium of around 6-20 cm thickness, typically grows moss, sedums, herbs and grass and requires less maintenance. The intensive green roof needs a thicker depth of growing medium of about 20-100 cm, requires irrigation and permanent

TOC

maintenance. The semi-intensive green roof is a combination of the extensive and intensive types; however, the extensive type must represent 25% or less of the total green roof area (see Table 6.1).

	Extensive green roof	Semi-intensive green roof	Intensive green roof
Maintenance	Low	Periodically	High
Irrigation	No	Periodically	Regularly
Plant communities	Moss, sedum, herbs and grasses	Grass, herbs and shrubs	Lawn or perennials, shrubs and trees
System build-up height	60 - 200 mm	120 - 250 mm	150 - 400 mm on underground garages > 1000 mm
Weight	60 - 150 kg/m^2	120 - 200 kg/m^2	180 - 500 kg/m^2
Costs	Low	Middle	High
Use	Ecological protection layer	Designed green roof	Park-like garden

TABLE 6.1 Classification of green roofs according to type of usage, construction factors and maintenance requirements [8].

Since the past three decades, in Europe and subsequently in North America, an expansion of green roof research and product development has been observed resulting in the publication of guidelines and standards for establishment methods and maintenance of green roofs. The most well-known and comprehensive set of guidelines for green roofs throughout Europe is the FLL guideline which was launched in 1982 in Germany and then translated into English in 2002 [9]. Since then a considerable number of studies, using different research methods like field experiments, numerical calculations or laboratory experiments, have been published. The benefits of green roofs for the urban-scale and the micro-scale are numerous. These include storm water management, extension of roof life, noise reduction, mitigation of urban heat island effect, and an increase of biodiversity. Other advantages include enhanced thermal performance and building energy efficiency, which are also the main focus of this study.

TOC

The climate conditions on rooftops are more severe compared to the conditions on ground level, which makes it more difficult for plants to grow or survive. Sedums are the most common type of ground covering plants on extensive green roofs. They are drought-resistant and offer a good coverage across the roof, providing minimum maintenance and easy installation [7]. However, it is important to find a balance between the survivability of species and green roofs' ability to provide valuable multiple services for the building and the surrounding ecosystem such as indoor air temperature reduction or enhanced biodiversity.

§ 6.3.1.2 The impact of green roofs on temperature and heat flux

With regard to the thermal effect of vegetation, there are many parameters that have an effect on a green roof's performance: vegetation form, type and diversity, coverage ratio (CR), leaf area index (LAI), foliage height and plant's biological processes like photosynthesis, respiration and transpiration. Additionally, physical features of the growing medium like thickness, water content and density, as well as the site conditions including climate factors and roof insulation value, can also determine the impact of green roofs on temperature and heat flux.

Evapo-transpiratory effect

Evapotranspiration is one of the most important factors contributing effectively on the cooling potential of green roofs. It is the combination of two phenomena: evaporation and transpiration. The physical process in which water transfers from soil into the atmosphere is called evaporation. Transpiration is a physiological process in plants through which water escapes through the stomata on leaves or the pores of the skin into the environment. The evapotranspiration in green roofs depends on the characteristics of the canopy, growing medium and environmental factors. The experimental result by Feng et al. [10] revealed that from the total amount of heat gained by an extensive green roof, 58.4% is released through evapotranspiration process, 9.5% is used for photosynthesis; the remaining part is either released to the atmosphere by long-wave radiative exchange between the canopy and the environment or absorbed by the growing medium. In line with the previous study, Lazzarin et al. [11] found the cooling role of evapotranspiration very effective. Based on their field experiment, in case of dry substrate when the evapotranspiration is very limited, a green roof reduced the heat gain by 60%, mostly due to solar reflection and absorption by the canopy and the growing medium. For a wet substrate, instead of 40% entering heat flux into the building, a slight outgoing heat flux resulted due to an increase in evapotranspiration rate.

TOC

Environmental factors also play an important role in the cooling effect of green roofs. Theodosiou [12] addresses the importance of wind speed and relative humidity (RH) for the cooling ability of green roofs. He explains that a dry environment increases the evapotranspiration rate, while wind accelerates this trend by removing humidity from the vicinity of vegetation, therefore enhancing the cooling effect. In line with the previous study, Tsang & Jim [13] measured the highest amount of transpiration during early autumn when the weather is dry and solar radiation is considerably high.

Shading effect

Wong et al. [14] carried out a field experiment on top of a low-rise building with an intensive green roof, covered with grass, shrubs and trees in order to measure the direct (roof surface temperature and heat flux) impact of rooftop greening in a tropical climate, Singapore. During the afternoon with high solar radiation (1400 W/ m^2), maximum surface temperate for the bare roof was around 57 °C, considerably higher than 42 °C for bare soil and 25.6 °C under a dense vegetation layer. Similar conclusions were achieved by Morau et al. [15] through a field study in a tropical humid island on the southern hemisphere. The results demonstrated that the surface temperature differences under an extensive green roof was considerably lower (73-35=38 K), and the heat flow was reduced in a range between 51-63%. Depending on the growing ability of different species (coverage ratio) and their shading coefficient, the efficiency of green roofs could be slightly different for each study.

Based on mathematical calculations, Barrio [16] found that leaf area index (LAI) and leaf angle distribution (LAD) are two important factors, reducing the solar radiation through the canopy effectively. LAI is a measurement index for canopy foliage density and is broadly defined as the total amount of leaf area (m^2) in a canopy per unit ground area (m^2). LAI ranges from zero for bare ground to over fifteen for coniferous canopies. The second important physical characteristic of plant canopy, LAD refers to the angular orientation of the leaves. In Barrio's experiment, the results show that plant species with large foliage and horizontal leaves have the most solar shading effect. Furthermore, Wong et al. [14] measured the impact of foliage density on heat gain/lost during a typical day. There was no heat gain observed under dense foliage (shrubs) during the whole day and the maximum amount of heat lost was also achieved by utilizing shrubs. According to Schumann [17], green roofs with higher LAI reduce higher amount of solar radiation that passes through the canopy. She found that increasing the LAI from one to five can reduce solar transmittance from 40% to 5%. Sailor et al. [18] suggested that in cooling dominated climates, LAI is the most important parameter which helps to reduce cooling needs, mostly through foliage transpiration and solar shading. Similarly, Jaffal et al. [19] developed a model for a green roof's thermal behaviour. They considered four values of LAI (0.5, 2, 3.5 and 5). Their results show that increasing the value of LAI will lead to a reduction of summer indoor air temperature and cooling demand. Wong et al. [20] found a lower temperature under a thick canopy layer and conversely a higher temperature under sparse foliage ranging from 26.5 °C to 36 °C. In line with the previous studies, the result of a mathematical model developed by Kumar & Kaushik [21] conforms that the heat flux through the green roof and the indoor air temperature will reduce by increasing the density of the foliage (or leaf area index).

Fang [22] provided an indoor controlled environment to plot a map that shows the correlation between coverage ratio (CR) and total leaf thickness (TLT) and their effects on indoor air temperature reduction in summer. He found that for a smaller percentage of vegetation coverage, a higher TLT was needed for thermal reduction; therefore, these factors have a complementary correlation.

Thermal insulation

Many researchers investigated the effect of different growing medium parameters on the thermal efficiency of green roofs, including the thickness of the growing medium, its relative density, along with the moisture content. A comparison was made by Permpituck & Namprakai [23] between two sets of green roofs with 10 and 20 cm soil thickness and a bare roof. Their result shows a significant reduction in heat transfer (59% and 96%) and energy consumption (31% and 37%) respectively for 10 and 20 cm soil depth compared to a bare roof. Other researchers also emphasise the importance of soil thickness on reducing the heat flux through a green roof similar to the study by Sailor et al. [18].

In other studies, Tsang & Jim [13] conducted a theoretical model to estimate the thermal performance of a green roof in the tropical climate of Hong Kong. Through a sensitivity analysis, they found that albedo value of the green surface, air convection rate near the canopy and the water content of growing medium are the three main factors that can regulate heat storage in a green roof. Halving the albedo value increasing heat storage by more than 70%. Furthermore, increasing the air convection rate near the canopy can effectively enhance evapotranspiration from the foliage and soil layer, hence improve the latent heat dissipation. The result shows that increasing the air rate from 12 to 16 m/s, will reduce the heat storage 45%. Finally, they found a 24% heat storage reduction when the moisture content of the growing medium increased from 30% to 60%.

TOC

The water content of growing medium influences the thermal performance of a green roof in each season in a different way. During the hot seasons or in equatorial climates (where the summer-winter temperature differences is not considerable), a wet green roof can increase the heat dissipation through evapo-transpiratory cooling. Therefore, it reduces the need for indoor cooling [16]. However, in winter, thermal resistance of a green roof improves with less water content in the growing medium [24] due to water having a higher thermal conductivity than air [25]. Through a predictive numerical model developed by Lazzarin et al. [11] similar conclusions were achieved for winter conditions. They found that a wet green roof has 40% more outgoing heat flux compared to a typical insulated roof. Although, Lazzarin et al. might not include cold winters where plants go dormant, thus there is no plant transpiration and there is just evaporation from the soil.

Del Barrio [16] found that a reduction in soil density leads to additional air pockets inside the soil, which in turn improves the thermal insulation properties of the soil layer. Similar conclusions by Lin & Lin [26] confirmed the findings of Del Barrio. Among four different plant substrates, the one with highest porosity provides the best thermal insulation for the green roof due to the formation of air pockets and water holding capacity. Based on other studies, there are evidences that green roofs with higher diversity and complexity (different plant type form and size) demonstrate lower temperature fluctuations below their canopy and enhance the roof insulation through the formation of air pockets. According to Wong et al. [14], similar amount of heat flux was measured for a roof covered with bare soil and with plants at night. It indicates that foliage has limited effect on outgoing heat flux during nights compared to growing mediums that have better thermal insulation properties. Therefore, it could be assumed that the thermal insulation properties of a green roof are mostly connected to the insulation properties of the growing medium than foliage.

§ 6.3.1.3 The energy impact of green roofs on HVAC systems

A well-insulated one storey office building is modelled by Ascione et al. [27] to investigate green roofs' potential on reducing the energy demand for air-conditioning systems in European climates. Based on the modelling results in cooling dominant climates for example in Spain and Italy, green roofs can reduce the annual primary energy demand (for cooling & heating) by maximum 8-11%. In heating dominant climates like the Netherland, UK and Norway, the maximum annual energy reduction is between 6-7%. In a mediterranean climate, Santamouris et al. [28] carried out a modelling on a two-storey air-conditioned nursery building. The energy saving potential of a green roof system with 40% CR was simulated for the top floor and for the whole building. They

TOC

found the monthly cooling load reduction for the whole building between 6-33% and more effectively for the top floor in the range of 12-76% when the building is insulated. These large energy saving differences can be influenced by several factors in simulation settings like the value of roof insulation, building dimensions, ratio of window to wall, green roof components and climate conditions. Moreover, based on their experiment, green roofs slightly increase the heating demand (3-9%) for a bare roof with insulation (due to a small amount of evapotranspiration) but reduce the heating demand for a non-insulated bare roof. Apparently, the improved insulation properties by adding a layer of green roof was higher than the outgoing heat flux resulted due to an increase in evapotranspiration rate for a non-insulated bare roof.

In accordance with the previous study, Jaffal et al. [19] conducted simulations on a single-family house with roof insulation in three European cities (Athens, La Rochelle and Stockholm). While green roofs have no impact on the heating demand in temperate climates, an increase of 8% was observed in mediterranean climates. This increase occurs as a result of shading and evapotranspiration effect of roof greening. However, in Stockholm with a higher latitude and a colder climate, the additional insulation effect of the green roof reduced the heating demand by 8%. This means in cold climates where plants go dormant, the impact of shading and evapotranspiration is negligible compared to insulation effect. Furthermore, their investigation regarding the cooling effect of green roofs shows a dramatic reduction of cooling demand in Athens by around 52% (13.9 kWh/m^2). In La Rochelle, the reduction was less significant in absolute value (2.4 kWh/m^2) but it was higher in relative value (96%). In Stockholm, the cooling demand is negligible, therefore the green roof has no impact on the cooling demand.

As it was mentioned before, roof insulation level can influence the thermal performance of a green roof considerably. The correlation between a building's roof insulation and the energy saving potential provided by green roofs has been investigated by many researchers. In a temperate climate, Jaffal et al.'s [19] experiment on the impact of roof insulation shows a heating demand reduction of 48% for the uninsulated green roof. However, by adding a 10 cm insulation layer the thermal effect of the green roof on the heating demand becomes negligible. Furthermore, the effect of a green roof on total energy demand decreases with higher levels of roof insulation. The total energy demand reduced from 50% for non-insulated green roof to 3% for the building with 30 cm of insulation below the green roof. According to another simulation study reported 12 years earlier in a mediterranean climate by Niachou et al. [29], the energy saving for cooling and heating load both are estimated around 45% when the roof has no insulation layer. However, by adding a thick layer of insulation, green roofs' energy saving percentage dropped surprisingly to 0% for cooling load and 2% for heating.

TOC

Other studies show the same trend, although the figures were slightly different. The limitations of building energy modelling software (boundary conditions, crudeness of the assumptions) combined with their paradigm shift in the current years can cause little discrepancies in studies reported earlier. Generally, it can be summarized that old buildings with poor insulation level could receive the highest energy saving by utilizing green roofs. However, this does not mean that a green roof individually can act as an insulation layer for a roof especially in cold climates.

Ascione et al. [27] analyse the economic feasibility of green roofs compared to a cool roof in six European cities from cold northern cities to hot southern mediterranean areas. They concluded that green roofs are not an economic energy efficient strategy in European climates, when considering the investment and maintenance costs. However other large-scale benefits on UHI, air pollution or rainwater management could justify the application of green roofs.

§ 6.3.2 Vertical greening

§ 6.3.2.1 Introduction

The greening of building facades has been suggested as a promising solution to make dense cities more sustainable [30]. Typically, the vertical skin of buildings is larger than the roof area. This fact emphasizes the importance of vertical greening systems, specifically for tall building typologies. The concept of vertical greening dates back to Babylonian civilization and the construction of the Hanging Gardens. Although, the application of climbing plants over a wall is not a new trend, the systems and the purpose of using them has changed over the last few decades. Historically, green walls were used for ornamental or horticultural purposes [31] but currently vertical greening systems, in line with other passive techniques, are used for their sustainability benefits.

When searching for the most appropriate vertical greening concepts for energy-saving, it is important to consider the type of system along with the influential factors on its operation. Currently, vertical greening systems can be classified into two main groups according to their establishment method, maintenance and operation: green façades and living walls. Living walls compared to green facades have a more complex structure including special supporting elements, growing media and irrigation systems to serve a large diversity of plants. Therefore, they are usually more expensive and require higher maintenance [32]. However due to the modular structure of living walls, plants can be pre-cultivated and then transferred to their place, as a result of which they can grow more efficiently [33]. In addition, in case of any mortality in one module, the proposed section can be replaced easily. As can be seen, the definition of each vertical greening system is described in Table 6.2.

GREEN WALL SYSTEM		Definition	Characteristics
Green façade	**Direct façade greening**	This is counted as the traditional way of greening facades. In this system climbing plants are directly connected to the façade and using building materials as a support. Plants are mainly rooted in the ground or planter boxes.	Climbing plants can hardly grow up to 25m without supporting structure and it takes a long time. They accelerate façade materials deterioration and make maintenance more difficult.
	Indirect façade greening	In this system for providing a gap between the façade and the green layer, some structural supports e.g. wire, mesh or trellis are used. Plants can root in the ground, on the roof or in substrates attached to the wall.	Double skin green façade increases the insulation properties of green walls by introducing a stagnant air layer between wall and green layer, protects the facade materials from demolition and supports plants to grow faster.
Living wall	**Living wall**	Living walls consist of modular pre-cultivated panels; each contains a growing medium and irrigation system to provide all of the nutrients for plants. They have also a waterproof layer to isolate the façade from moisture penetration.	In these systems a large variety of plants can be added including ferns, small shrubs, and perennial flower. If necessary, the modular structure makes the replacement of plants easier. These systems need a high maintenance and are more expensive compared to green facades.
	Indoor living wall (Bio-filters)	Bio-walls are indoor vertical greening systems that are mostly used for filtration of the indoor air and enhancement of aesthetic values of the indoor environment especially in office spaces. They can purify the air passively through natural convection or by using a fan to facilitate the circulation and improve its efficiency.	

TABLE 6.2 Vertical greening systems, definitions and their characteristics [32, 34].

§ 6.3.2.2 The impact of green walls on temperature and heat flux

Three main factors are recognized by researchers as the key parameters which determine the impact of vertical greening systems as a passive technique for energy saving in a building: the cooling effect of vegetation and substrate through evapotranspiration, the thermal insulation effect through making a microclimate environment between the canopy and building envelope and the shadow effect of the vegetation layer.

Evapo-transpiratory effect

Wong et al. [35] conducted a field work to observe the influence of different vertical greening systems on ambient air temperature. The best cooling effect was measured in the vicinity of living wall system with a reduction of 3.3 °C and 1.6 °C respectively at the distance of 15 and 30 cm from the green wall. For up to 60 cm, all of the vertical greenery systems have no longer influenced the ambient temperature. This indicates that a green facade becomes less hot compared to a bare wall, hence not only radiates less heat but also cool the ambient environment through evapotranspiration. Consequently, a cooler ambient temperature around a building can translate to a decrease in the cooling load of the building. They also found that, with appropriate use of greenery on buildings, the micro-climate can improve noticeably. Perini et al. [34] have also measured the ambient air temperature differences in the vicinity of three vertical greening systems (direct, indirect and LW). The results show no remarkable air temperature differences for all of the greening systems at the distance of 10 cm to one meter away from the façade. These differences between two studies can be explained by the influence of environmental factors on evapotranspiration rate. In Perini et al.'s experiment, the measurements were carried out in a temperate climate during autumn when direct solar radiation is considerably low, therefore plant's transpiration would be little compared to the hot summer conditions.

Vertical greening systems can reduce the indoor air temperature by evapo-transpiratory cooling effect of vegetation layer or growing media. By doing so, the cooling load of the building can be reduced. Through a field work, Sunakorn & Yimprayoon [36] measured the indoor air temperature differences for two west oriented rooms one with indirect vertical greening system and a room without. The green wall was made from climbing plants with 4-5 LAI and 90% coverage, with 70 cm distance from the wall. The experiment was done at the beginning of summer in a hot and humid tropical climate. To assess the impact of wind velocity on the thermal performance of vertical greening system, two scenarios of ventilation were applied: with natural ventilation and without ventilation. The average indoor air temperature differences between the two

TOC

rooms for ventilated and not ventilated scenarios were 0.9 K and 0.3 K respectively. It shows that using natural ventilation can slightly improve the cooling effect of vertical greening system due to higher evapotranspiration rate. The result of Chen et al. [37] study confirms the previous findings. In a lab environment with no ventilation, the mean temperature of the indoor space only reduced by 0.4 °C through the application of living wall system (LWS).

Indoor active living walls have been suggested as a good alternative for improving the building's indoor air quality. These systems can work individually or together with the air-conditioning systems. Although their installation and maintenance are expensive and complex, they can provide the same benefits as passive living walls [38]. The cooling effect of indoor living walls results from the combination of evaporation from constant irrigation and transpiration from vegetation. Moreover, their capacity in Oxygen production and bio-filtration of volatile organic compounds (VOCs) and CO_2, reduce the need for air filtration [39].

A field experiment was carried out by Fernández-Cañero et al. [40] in a mediterranean climate, Spain. They installed an indoor living wall with four different substrates (two from organic origin and two synthetic) to determine their impact on indoor air temperature and humidity. The experiment was carried out during a warm period of the year when the building was occupied by normal activities. Their measurements of the variation in indoor air temperature show a reduction of the ambient air temperature by 4 °C. The temperature reduction was most remarkable in the vicinity of the vegetation with a fall up to 7 °C. In addition, an average increase in indoor humidity near the living wall of around 15% was observed. By taking into account the role of living walls in the humidification and the cooling of the indoor environment, they can contribute in providing comfortable conditions for the occupants, reducing the need for air-conditioning systems especially in hot and dry climates.

Shading effect

A green wall can protect the building envelope from overheating through shading. The total solar radiation striking a green wall depends on the physical characteristics of the canopy, it will be transferred into these three ways: reflected to the atmosphere or absorbed by the canopy or transmitted through the leaf [41]. The shading effect of a vertical greening system depends strongly on the density of the foliage and the coverage ratio. An experiment was setup by Ip et al. [42] to investigate the shading coefficient of a deciduous climbing plants that covered the southwest windows of a building in the temperate climate of the UK. The results showed solar transmittance through one leaf layer initially being around 45%, dropped to 12% when it passed over five leaf layers.

TOC

There are some studies indicating the role of plant's shading coefficient in ameliorating the thermal performance of a building. Overall thermal transfer value (OTTV) is an indicator for the thermal performance of a building envelope. According to Building Control Regulations published in 1979, all air-conditioned buildings are required to be designed with an OTTV of not more than 45 W/m^2 [43]. Wong et al. [44] simulated the effect of vertical greening systems on the OTTV of a 20-storey hypothetical building that is fully covered by glass. They found that building's OTTV reduced significantly (40%) when the plants coverage ratio was 50%, and the solar transmittance value was only 4%. By increasing the shading coefficient from 0.5 to 0.98, the envelop OTTV reduced to 21% and 0.6%. Furthermore, they plotted a linear correlation between shading coefficient and LAI. It means that the higher value of LAI can be translated to less solar transmittance, hence grater thermal performance for the building.

Shading by vertical greenery systems leads to a reduction of external surface temperature and the consequent incoming heat flux through building envelope. Wong et al. [35] conducted a field work to observe the influence of different vertical greening systems on the surface temperature of nine free standing concrete walls in an open environment in Singapore. The substrate thickness and the foliage height were different in each vertical system. The maximum reduction observed on a sunny day was around 10.9 °C for living walls with modular panels. However, it should be noticed that in this study both sides of the concrete wall are exposed to outdoor climate conditions. Therefore, the observed figures may be slightly different for a real building. For example, based on a field measurement, Chen et al. [37] have addressed the cooling effect of LWS on the exterior wall more effective by a maximum reduction of 20.8 °C compared to the bare wall in a hot and humid conditions.

A field experiment in the mediterranean continental climate of Spain was performed by Nori et al. [45] to determine the efficiency of an LWS on the exterior wall of a highly insulated building both in a sunny day and a cloudy day. They found the efficiency of an LWS is extremely influenced by solar radiation intensity. On a sunny day with a maximum vertical radiation of 692 W/m^{2}K, the highest recorded temperature was 46.7 °C for the conventional façade, and 22.1 °C for the green façade. In a cloudy day with less solar radiation (MVR: 140.8 W/m^{2}K), the temperature differences between the two façades was only 3.1 K. Mazzali et al. [46] also reported the external surface temperature differences of three LWSs with a range between 1 K (a cloudy day) to 20 K (a sunny day) affected by the amount of solar radiation. Thus, a green wall can improve the building's thermal performance in a different range, depending on the outdoor conditions and, more importantly, the solar radiation (sky clearness and radiation angular distribution).

Perini et al. [34] conducted a field measurement in the Netherlands, a temperate climate, and compared the surface temperature differences between a bare wall and three different vertical greening systems. Small temperature differences were obtained for indirect (20 cm air cavity) and direct (attached) green walls. Living wall systems with planter boxes, compared to other greenery systems, had a higher temperature difference of around 5 K. Among nine different green wall systems in Wong et al.'s study, LWS with modular panels contribute more effectively on surface wall temperature reduction [35]. This is likely caused by higher shading effect by planter boxes beside higher evapotranspiration duo to constant irrigation in living wall systems.

Thermal insulation

The formulation of microclimate environment in the air cavity between a building façade and a green wall, acting as a thermal buffer, hence reducing the heat flux through the building envelope by regulating the ambient air temperature and wind speed. According to Nori et al. [45], a green façade has higher surface temperature compared to a bare façade during night times when there is no solar radiation. This can be translated into the thermal buffering ability of intermediate microclimate and its influence on deceleration of the heat loss through the building envelope.

Pérez et al. [47] conducted a field work on a detached green wall, assembled on a steel structure with 80-150 cm distance form northwest, southwest and southeast façade in the dry mediterranean continental climate. The study was done during spring and winter when the foliage coverage was around 62%. The amount of transmittance through the foliage range from 37% in spring to 3% in summer when the green wall has the highest coverage ratio. Furthermore, they measured the role of microclimate environment in the intermediate spaces. They found lower temperatures (maximum 2 °C) and higher humidity (maximum 7%) in the intermediate space compared to the ambient environment. Other authors have also addressed a similar trend for temperature reduction in the intermediate space of a LWS, as with the study by Chen at al. [37]. In this study, they observed the influence of natural ventilation and the air cavity thickness on the cooling effect of microclimate environment in the intermediate space. The maximum temperature reduction of air cavity was found around 9.7 °C for the LWS that was sealed in all directions and located with 3 cm distance from the wall.

Perini et al. [34] have also investigated the correlation of air cavity thickness with thermal insulation properties provided by green walls. They found that direct façade greening and living wall (with 4 cm air cavity) are more effective on reducing the wind speed around the building façade than indirect green wall (with 20 cm air cavity) due to shorter vegetation-wall distances. They also noted that a reduction of the air layer

TOC

thickness of an indirect greening system by around 4-6 cm would improve its thermal insulation impact on building.

§ 6.3.2.3 The energy impact of green walls on HVAC systems

Green facades can contribute effectively in reducing the indoor temperature by absorbing the solar radiation for growth and biological processes. A reduction of indoor air temperature means a considerable energy-saving for air-conditioning during summer times. However, shading by plants should not obstruct the passive heat gain through the building envelope during winter times otherwise it will increase the heating demand. Kontoleon & Eumorfopoulou [48] modelled a green wall with 20 cm thickness on four main directions of a building in the Greek region during summer to predict the influence of green wall's orientation on reducing the cooling demand in a mediterranean climate. The highest and lowest influence was acquired through greening the west- and north-oriented walls with 20% and 5% energy saving respectively. Therefore, selecting the wright orientation for plants on vertical surfaces can result in a remarkable energy saving for cooling loads during summer.

McPherson et al. [49] conducted a simulation study in four different climates to investigate the shading effect of vegetation on all surfaces (both roof and walls) on the energy demand of a building. They found that in cold climates the shading effect from an evergreen plant increases the annual heating cost by 21%. If deciduous plants were used, this negative effect was diminished. Therefore, green roofs and walls can increase or decrease the building heating demand, depending on the winter outdoor conditions and, more importantly, the solar radiation (sky clearness and radiation angular distribution). Furthermore, in temperate and hot climates, dense shading over all surfaces of a building reduces the annual cooling cost by 53-61%.

Through a computer modelling, Stec et al. [50] showed that the application of vegetation inside the cavity of a double skin façade can provide a comfortable indoor climate for a building. They compared the thermal performance of two shading devices inside a double-skin façade: a bio-shade and a blind. The result shows a lower temperature on the surface of the green layer (35 °C) compared to the blinds (55 °C) and up to 20% reduction in the energy use of air-conditioning systems.

§ 6.3.3 Green balconies

§ 6.3.3.1 Introduction

A balcony is commonly defined as a platform that projects from the wall of a building and is surrounded by a railing, balustrade, or parapet. Haber [51] conducted a post-occupancy study on a high-rise building and found that most of the complaints by high-rise dwellers originated from a lack of greenery and a sense of disconnection form the outside. Balconies can function as a mediator space to connect the indoor with the outdoor environment. They offer many benefits and advantages both for the people who live inside a building and for the ecosystem. Balconies can provide a spectacular view to the city, urban park or natural greenery. They also enhance biodiversity and architectural interest and help to reduce rain water runoff. There are also some studies which indicate that balconies can add to the value of a building compared to a similar construction without balconies [52]. Over the last decades, new technologies have provided conditions for growing large trees up to three meters with a thick substrate of soil (1 meter) on balconies (e.g. Milan vertical forest project in Italy).

Besides all of the advantages that balconies offer a building, they can negatively contribute to heat gains and losses; and as a consequence, increase the heating and cooling load for air conditioning systems. Balconies can act as a thermal bridge between the indoor and outdoor environment. According to energy simulations done by Ge et al. [53] on a balcony in a cold climate of Toronto, reducing the heat transfer through the balcony slab can decrease the heating and cooling demand by 5-13% and 1% respectively.

§ 6.3.3.2 The impact of green balconies on temperature and heat flux

There has been limited research on a green balcony's contribution to energy saving for buildings. However, the number of studies that investigates the cooling or shading effect of neighbouring trees on a building is considerable. Therefore, the aim is to fill these gaps through reviewing the studies that might provide the same benefits for balconies such as shading trees nearby a building façade. There are many studies that show the application of plants around buildings, especially in front of the south elevation that can reduce peak energy consumption through controlling the solar radiation on a wall.

Evapo-transpiratory effect

Through a field experiment in a mediterranean climate, Papadakis et al. [54] measured the role of deciduous trees on regulating the microclimate environment when facing a southern elevation. The ambient air temperature was maximum 3 °C lower and the relative humidity was up to 7% higher in the shaded area near the building façade.

Shading effect

Papadakis et al. [54] further studied the shading effect provided by trees on the wall. In their study, they compared two areas of an office building during summer: a shaded area with an un-shaded area. The peak solar radiation over the exposed area was measured around 600 W/m^2 though the corresponding value for shaded wall was less than 100 W/m^2. Berry et al. [55] carried out a field work on three identical building during summer and spring in southern hemisphere in Melbourne with an oceanic climate. As a reference one building was exposed but the west and north facing walls of the other two buildings were shaded separately by deciduous and evergreen potted trees. They used the collected data from field measurements to develop a model that predicted external wall surface temperature. According to their findings, both shading coverage and solar irradiance are the two main factors for quantifying the external wall temperature through the predictive model. Furthermore, the presence of shading trees can reduce the wall surface temperature and the ambient air temperature (within the intermediate space of wall and tree) up to 9 °C and 1 °C respectively.

Thermal insulation

McPherson et al. [49] simulated the effect of a vegetation layer on the thermal performance of a building as an insulation against wind. Modelling result presented a 50% reduction of wind speed nearby the building façade while it passed through a shading tree. Some studies have mentioned the insulation effect of shading trees during nights. According to Papadakis et al. [54] study, the wall surface temperature was slightly higher (0.5-1 °C) in the vicinity of vegetation during the nights. This shows that the vegetation layer is a barrier against heat radiation from the building envelope to the atmosphere during the night, hence reducing the UHI. A similar trend was addressed in Berry et al.'s field experiment [55]. They found the air temperature between the wall and the shading tree, slightly warmer during the night (up to 1 °C) compared to the area without trees.

§ 6.3.3.3 The energy impact of green balconies (shading trees) on HVAC systems

Shaded trees can make a microclimate close to the building façade through evapotranspiration, shading effect and wind control. It means that they can reduce the indoor air temperature, hence reducing the energy need for space cooling. However, choosing the wrong configuration of shading trees either the orientation or the type of plants can result in a higher heating demand in winter. Several experimental and modelling studies have investigated the role of shading trees on building energy consumption. Many variables can influence the cooling potential of shading trees such as the number, height and orientation of trees, the distance of trees from the building, their coverage percentage over walls and roof, the density of foliage, the shading coefficient and the variability of experimented building designs.

Huang et al. [56] simulated the energy impact of 3 shading trees on summer cooling of residential buildings in different US cities. The highest energy saving was gained for Sacramento with mediterranean climate. The simulation results suggested that shading on building can reduce annual cooling load by 53% for Sacramento with 904 cooling hours demand. In subtropical desert climate of Phoenix with hot and dry summer (3647 cooling hours demand), the higher air temperatures may have negated the cooling effect of the shade with less energy saving by around 34%. The calculated energy saving for Los Angeles was the least among all the climates due to insignificant requirement for cooling with 64 hours during a year.

However according to another study, in the cold climate of Canada, the modelling results showed that the annual cooling demand can be reduced by 90% in relative value [57]. For two monitored houses in Sacramento, Akbari et al. [58] simulated the energy saving for summer cooling by around 30% through shading the southern and western facing walls by sixteen trees. Simulation results by Simpson & McPherson [59], shows energy savings up to 50% for cooling when shading trees are located in all directions except north in the mediterranean climate of California. In their simulation it was assumed that a deciduous tree can block 85% of solar radiation during the summer which is a high shading coefficient.

Based on empirical measurements, Pandit & Laband [60] developed a statistical model that the electricity saving by shading trees could be estimated. Predictive results showed more than 14% energy saving for electricity consumption by a dense shade covering 50% of a typical house area during summer. However, in winter conditions with less shading coverage (20%), electricity usage increased by 6% which might be due to less solar heat gain through building envelope and more dependence on artificial lightning instead of natural light in dark winter days. The modelling result by Nikoofard et al. [57] showed almost the same trend for winter conditions with an increase in heating demand by 10%.

The result of a field experiment by Laband & Sophocleus [61] reported the cooling potential of shading trees more significant compared to computer simulations. They compared the electricity consumption of two identical buildings one exposed and the other shaded during hot times of the year. They set the indoor air temperature on 22 °C and use air conditioning units for cooling the indoor air. The AC units were directly connected into data loggers to measure electricity consumption for each building. It was found that for the exposed building, the electricity usage for indoor cooling was 2.6 times more than the shaded building. However, it is not possible to generalize these finding, as the energy saving might be varied in case of any change in roof colour, or insulation level.

A few studies have investigated the configuration of canopies with the aim to achieve the highest energy saving. McPherson et al. [49] suggested that in cold climates the orientation of planting should be in such a way that it reduces the cold winter wind and provides direct solar radiation to southern and eastern walls. In the temperate climate, the same trend emerged, although the vegetation layer should not block the summer winds. In contrast, in hot climates, both shading and wind velocity should be enhanced by using an appropriate type of plants. Simpson & McPherson [59] simulated the energy impact of shading trees on building air-conditioning in California. The largest annual and peak energy saving gained by shading the west-facing walls. Pandit & Laband [60] highlighted shading density as an important factor besides shading coverage. With the same value for shading coverage, a dense shade can provide more cooling effect compared to moderate or light shade. However, in order to provide a better shading, trees should be close and tall enough to shade the external walls and possibly the roof.

§ 6.3.4 Sky gardens

Over the last decades, sky gardens (Sky courts or podium gardens) have been introduced as a new greenery concept mostly integrated into high-rise buildings. There are different definitions for sky gardens. Osmundson [62] defines it as a vegetated open space that may be located at any height and is separated from the ground level by a man-made structure to provide benefits for the environment and for humans. Ong [63] defines a sky garden as a green space that is located above the ground level and can be in the form of a podium garden on intermediate floors of a building or a roof garden at rooftop level.

TOC

Through reviewing some examples of green high-rise projects over the world, the three most common places in buildings where sky gardening is applied are: on a structure on top of the roof, on intermediate floors (on podiums) and on the sky bridges.

There are some differences between a common green roof system and a rooftop garden due to differences in accessibility and exposure to sun and wind. In sky gardens, the rooftop greenery system is usually placed on an external structure with some distance to the roof of the building (e.g. Marina bay sands hotel in Singapore). Between the three aforementioned locations for sky gardens, rooftop garden and sky-bridge are not directly connected with building envelope. Consequently, they probably could not provide the same direct thermal benefits like the other greenery systems such as green roofs or green walls. However, sky gardens may offer most of the benefits provided by other greenery concepts for the macro scale such as mitigation of urban heat island effect, enhanced biodiversity and removal of air pollutants, as well as storm water management and visual aesthetic improvement [64]. However, if these systems are broadly integrated into buildings, they might have some indirect energy benefits through cooling the ambient air, thereby reducing the need for air conditioning systems. A podium garden acts like a green roof but on intermediate levels of a building. Consequently, podium gardens can offer the same benefits provided by green roofs for the building scale and the city scale. Only variations in climatic factors like solar radiation or wind speed may create differences concerning their performance.

Compared to other greenery concepts, there have been surprisingly few studies that explore the effect of sky gardens on the building and the outdoor environment. Tian & Jim [64] made a comparison between the distribution of two greenery systems, sky gardens and roof gardens, in the compact city of Hong Kong. They found that the total area of podium gardens was eight times higher compared with roof gardens. Easier accessibility, more visibility and less exposure to strong winds are some of the factors that make sky gardens more available in Hong Kong's high-rise buildings compared to green roofs. According to Tian & Jim "sky gardens in Hong Kong are in the early stage of development, with low green ratios in most land uses and districts" (p. 306) [64]. Some of the barriers which limit the wide proliferation of sky gardens are: Social and economic factors, lack of knowledge and awareness, lack of incentives from governments and private sectors, technical issues and risks associated with uncertainty especially for buildings with more than twenty floors.

TOC

§ 6.3.5 Indoor sky gardens (Indoor greening)

§ 6.3.5.1 Introduction

Indoor sky gardens are indoor spaces like atriums with more than one-storey height and usually equipped with potted plants or big trees in thick soil substrates. Indoor plants offer the building inhabitants some of the same benefits as the experience of outdoor nature. Improvement of comfort conditions is one among the numerous benefits indoor vegetation can provide for the tenants.

§ 6.3.5.2 The impact of indoor planting on indoor air quality

In urbanized societies, modern lifestyle caused people to spend over 80% of their time indoors for their daily activities [65]. Therefore, the importance of indoor air quality (IAQ) is growing due to its direct influence on human's health and productivity. Around 25% of US citizens suffer from poor IAQ either in their workplace or at home [66]. In Australia, unhealthy indoor air has been posed considerable finances around $12 billion annually due to workers absenteeism, less productivity and medical costs [67]. Globally, it is estimated that the number of deaths caused by poor IAQ is fourteen times higher than ambient air pollution [68]. As a result, US Environmental Protection Agency (EPA) determined IAQ as one of the top five public health concerns over the past decades [69].

Using ventilation (passive or active) can help to remove moisture and airborne pollutants from indoor spaces and provide health and comfort for the occupants. When a building is naturally ventilated through the openings (controlled) or the gaps around openings (uncontrolled infiltration), it is called passive ventilation. Active ventilation is referred to the application of mechanical devices for air extraction. Modern buildings are designed in a way that both passive leakage and active ventilation are reduced. Therefore, the potential for illnesses such as Sick Building Syndrome (SBS) increases. In Table 6.3 common air pollutants and their sources combined with sickness symptoms and the standard values for these pollutants are presented. Increasing the air change rate, removing air pollutants and purifying indoor air are effective solutions to cope with poor indoor air quality [69].

AIR POLLUTANTS	SOURCE	SICKNESS SYMPTOMS	ASHRAE STANDARD
Particles: dust, pollen, viruses, bacteria, moulds, fungi, cigarette smoke	Outdoor air, combustion, carpets, human activity, decaying building	Irritation to eyes and/or respiratory tissues, allergies, cancer, indirect effect through biological production of toxins.	Particles < 2.5 µm: 15 µg/m^3 Particles < 10 µm: 50 µg/m^3
Gaseous pollutants: CO, CO_2, NO_x, formaldehyde, VOCs	Combustion, human activity, building materials, furniture, cleaning products, mould development etc.	Irritation to eyes and/or respiratory tissues, allergies, cancer, effects on the respiratory liver, immune, reproductive and/or nervous system	CO < 9 ppm (8 h) CO_2 < 5000 ppm NO_2 < 100 µg/m^3 Formaldehyde < 0.1 mg/m^3 (30 min)
Radioactive gases	Rock, soil, groundwater, natural gas, mineral building materials	Lung cancer	Radon: 4 pci/litre

TABLE 6.3 Typical air pollutants in indoor environment [66, 70].

Indoor vegetation like potted plants contributes to the purification of indoor air through bio-filtration. Early findings have been demonstrating that potted plants can significantly contribute in air purification through their leaves [71]. Conversely, under chamber conditions in a lab experiment, Godish & Guindon [72] observed the highest air filtration occurred when plants were defoliated. They suggested air filtration have been associated with soil medium factors. According to Fjeld & Bonnevie "leaves, stems and roots work together with micro-organisms that live in the root zone, creating an ecosystem that can function as an air filtering system" (p. 6) [73]. In addition, through photosynthesis plants take up carbon dioxide from the indoor air and release oxygen. As a result, they might reduce the need for ventilation hence contributing in energy saving.

Knowles et al. [74] found that more than 80% of indoor contaminants such as VOCs and CO_2 can be removed through the use of indoor plants. In line with previous work, Tarran et al.'s [75] field measurements on sixty office buildings confirmed that potted plants can remarkably reduce total volatile organic compound (TVOC) loads in the indoor environment by 75%. Furthermore, they found the impact of air conditioning rate and indoor light intensity insignificant on the process of bio-filtration. Pennisi & van Iersel [76] performed a field experiment to define the reduction in ambient carbon dioxide levels resulting from the use of different species of indoor plants. They found that larger plants (mostly woody species) can take up higher quantities of CO_2 compared to smaller herbaceous species.

The result of a post-occupancy analysis by Fjeld et al. [77] showed that indoor vegetation can alleviate symptoms of discomfort among office workers resulting from SBS. The score sum of symptoms was collected from 51 office workers in two scenarios, one time with plants in their offices and one period without. The result shows an overall improvement of around 23% when the respondents had plants in their offices. They also found that plants can reduce workers' complaints on some issues more effectively for example coughing, fatigue and dry skin; each decreased by 37%, 30% and 23% respectively.

§ 6.3.5.3 The impact of indoor planting on users' perception

Taib & Abdullah [78] conducted a study on a 21-storey high-rise office building in Singapore to investigate user perception of three different types of greenery during the hottest period of the year. The greenery concepts included: an indoor sky garden (on the 10th floor), a green balcony (enclosed by three faces on the 12th floor) and a green roof (on the 21st floor). The first part of their study was on the usage of these green areas. Through a questionnaire survey they found that 96% of respondents agreed to the application of green spaces in high-rise office buildings. However, a different correlation seems to exist between respondents' desire to have greenery in their offices and the level of usage by them. Only half of respondents have visited the landscape gardens which shows a failure in their design.

An investigation of building design layouts shows that accessibility and visibility are two important factors which encourage people to use such green spaces. Therefore, while over half of respondents visited the indoor sky garden, less than one-fourth visited the green balcony and the green roof. According to Taib & Abdullah "these findings supported an earlier statement by Alexander et al. [79] that people will visit urban greenery on a regular basis if it is within three to five minutes' walk of their home/workplace" (p. 637) [78].

In addition, they found a correlation between the usage of green spaces and the comfort level. At the indoor sky garden which has the highest number of visitors, 53.9% of the participants felt comfortable. At the green balcony and the roof garden that had fewer visitors, respondents felt slightly comfortable respectively by 16.7% and 22.5%. Some of the respondents suggested that providing some shaded areas could create a more comfortable environment at the rooftop garden. Moreover, Taib & Abdullah [78] asked the respondents to prioritize their purpose of visiting green spaces. Interestingly, visitors use the green spaces with the same preferences. Their study illustrated that green areas in high-rise office buildings mostly are used for resting, refreshing and for social activities.

§ 6.3.5.4 The energy impact of indoor planting on HVAC systems

There is also some evidence that plants can increase the average humidity of the indoor air through evapotranspiration which may enhance the thermal comfort of the occupants, especially in hot interior spaces without ventilation. A study conducted by Lohr & Bummer [80] revealed that when plants were placed in offices without ventilation the relative humidity (RH) increased significantly by around 15%. They also showed that in a ventilated room plants only have a limited effect on average humidity (3-5%). However, it should be mentioned that in both of the cases, the amount of RH did not exceed the recommended range of thirty to sixty percent. Additionally, some plant species have a higher rate of transpiration. According to Fjeld & Bonnevie [73], plants with higher density and bigger leaf surface had a higher humidification effect.

§ 6.4 Discussion and conclusions

A literature review of the impact of greenery systems on thermal and energy performance of buildings demonstrates how little is known concerning the application of plants on areas like green balconies and sky gardens (indoor & outdoor). Over the last decades, sky gardens have been introduced as a new greenery concept mostly integrated into high-rise building designs. Since tall buildings have been the corner stone of our cities, it is important to do more research on these greenery concepts with a focus on energy impact. Furthermore, measurements on the impact of greenery systems have so far been limited to simulated models or filed studies on single buildings with time constraints. The variability of home design and occupant's behaviour in different studies make the generalization of results difficult. Using a large sample of homes with similar size and design strategies and possibly a longer period of study will help to have a more realistic overview on the energy impact of greenery systems in different climates.

In addition, a gap of knowledge exists in some areas that can be expanded in the future. Therefore, evaluating the effect of greenery systems on energy requires further study of:

- Finding the optimal configuration of plant position (greenery concept), plant form (leaf area index and plant height), foliage shading (an evergreen and a deciduous type) and substrate properties (thicknesses, moisture content and density) for different climate types.

- Developing steady state analysis under controlled conditions to determine the influence of study conditions (building usage, morphology and its insulation level) besides the climatic factors on greenery systems seasonal energy performance
- Studying the influence of integrating greenery systems on energy saving for buildings.
- Discussion on cost effectiveness of different greening systems

§ 6.4.1 Impact of greenery concepts on comfort

Indoor greenery concepts (indoor living walls and indoor sky gardens) mostly have benefits for indoor thermal comfort and specifically for indoor air quality (IAQ). According to this literature review, indoor plants can provide indoor comfort by means of three factors: purification, humidification and temperature reduction. Moreover, from a psychological point of view, plants can also provide comfort conditions by reducing stress and increasing health and well-being. The bio-filtration effect of leaves, stems and roots, can reduce the accumulation of VOCs in airtight buildings and provide a healthy environment for the building's occupants. Improving the indoor air quality leads to a reduction of the sick building syndrome, hence increasing the comfort and productivity of inhabitants. In addition, indoor plants can regulate the indoor temperature and humidity through evapotranspiration. Hot interior spaces without ventilation benefit most from this effect. Outdoor greenery systems such as green roofs, green walls, green balconies and sky podiums can also improve indoor thermal comfort through reducing heat fluxes and temperature fluctuations on building envelope. However, in case of horizontal greenery systems their effect would be limited to top floors.

§ 6.4.2 Impact of greenery concepts on energy

Greenery concepts can offer many benefits to a building. Among them, many researchers have been investigated the effect of different greenery systems on building energy consumption. Based on this literature review, greenery systems show different efficiencies over cooling and heating seasons. The maximum efficacy of greenery systems is reported during summer. Furthermore, in sunny days or places with higher solar radiation, the efficiency of greenery systems is reported higher. In contrast, for winter conditions, different studies suggest controversial conclusions regarding the greenery systems' performance. It means that they can both save the energy or increase the heating need depending on the study conditions.

ENERGY IMPACT			GREENERY SYSTEM				
			GR	GW	GB	SG	ISG
Summer cooling	Evapotranspiration	↑	[+] Leaf area index [+] Substrate moisture content	[+] Leaf area index [+] Substrate moisture content	[+] Leaf area index ****		[+] Leaf size [+] Irrigation
	Shading	↑	[+] Coverage ratio [+] Foliage size [+] leaf angle distribution (Horiz)*	[+] Coverage ratio [+] Leaf area index [+] Using LW system with planter boxes	[+] Shading coverage [+] Shading density [−] Wall-vegetation distance [+] tree height [+] Shading on west side		[N/A]
Winter heating	Evapotranspiration	↓	[−] Substrate moisture content**	[−] Substrate moisture content	[−] Substrate moisture content *****		[N/A]
	Shading	↓	[−] Shading coefficient (deciduous plants)	[−] Shading coefficient (deciduous plants)	[−] Shading on south and east sides		[N/A]
	Insulation	↑	[+] Substrate thickness [−] Substrate moisture content*** [+] Plant diversity [−] Substrate density	[−] Wall-vegetation distance	[+] high coverage in the direction of cold winter wind [−] Substrate moisture content		[N/A]

↑ The effect should improve; ↓ The effect should decrease;
[+] Higher value or quantity is needed; [−] Lower value or quantity is needed
GR: Green roof, GW: Green wall, GB: Green balcony, SG: Sky garden, ISG: Indoor sky garden
** Horizontal leaves have the most solar shading effect for green roofs*
*** In winter a dry growing medium has less evapotranspiration, hence reducing the outgoing heat flux*
**** A dry growing medium is a better insulator because water has higher thermal conductivity than air*
***** This part is based on the effect of nearby shading trees due to a gap of knowledge for green balconies and sky gardens*
****** The impact of substrate moisture content is more considerable for a podium garden which is in a direct connection with the building envelope and is negligible for green balcony and other forms of sky garden*

TABLE 6.4 The impact of greenery concepts on building energy consumption.

In cold climates when passive heat gain through the building envelope effectively contribute to energy saving, shading by vegetation will increase the heating demand. Furthermore, the age of building is an important factor. A large number of old buildings have poor insulation value. Then, adding an extra greenery layer can improve the insulation properties of buildings. As a result, when the positive effect of insulation by a greenery system is higher than the negative effect of shading, the application of greenery systems could lead to a reduction of heating load in winter.

The seasonal energy saving through application of greenery systems comes from three phenomena by plants or their substrate. While evapotranspiration and shading contribute effectively in the reduction of cooling load, the insulation effect of greenery systems can reduce winter heating demand. In Table 6.4 the contribution of influential plant or substrate-related factors in summer cooling and winter heating is summarized.

§ 6.4.3 Suitability of greenery concepts for different climates

The efficiency of greenery concepts also depends strongly on the climate factors such as temperature, relative humidity, solar radiation (sky clearness and radiation angular distribution) and wind velocity. A dry environment increases the evapotranspiration rate and wind accelerates this trend by removing humidity from the vicinity of vegetation. However, natural ventilation can reduce the thermal buffering ability of an indirect vertical greening system with long vegetation-wall distances. Furthermore, solar radiation is found the most important factor to influence the efficiency of greenery systems for summer cooling. Higher horizontal or vertical radiation means more temperature differences between the shaded and unshaded area, hence lower heat gain through the building envelope and more energy saving for cooling loads.

The geographical location of a place from the equator and cloud coverage determine the extent of heat gain through building surfaces. In places with high horizontal radiation (low latitude), application of green roofs is more beneficial for solar protection. In contrast, shading by vertical greenery systems is more applicable in places with high vertical radiation (high latitude). In Table 6.5 the best orientation for the application of greenery systems concerning different climate conditions is summarized.

TOC

COLD	TEMPERATE	TROPICAL	HOT AND DRY
The orientation of greenery systems should be in a way that it reduces the cold winter wind but provides direct solar radiation to south and east walls.	The vegetation layer should not block the summer winds but should reduce the cold winter wind. Furthermore, direct solar radiation to south wall and roof is necessary for places with high heating degree days.	Both shading and wind velocity should be enhanced by using an appropriate type of plants.	The highest amount of shading and evapo-transpiration is needed. Roof space, east and west walls are places that need the highest solar protection.

TABLE 6.5 Suitability of greenery concepts for different climates.

Appendix

The following part representing the list of references that are not cited in this paper but have been used to draw the conclusions:

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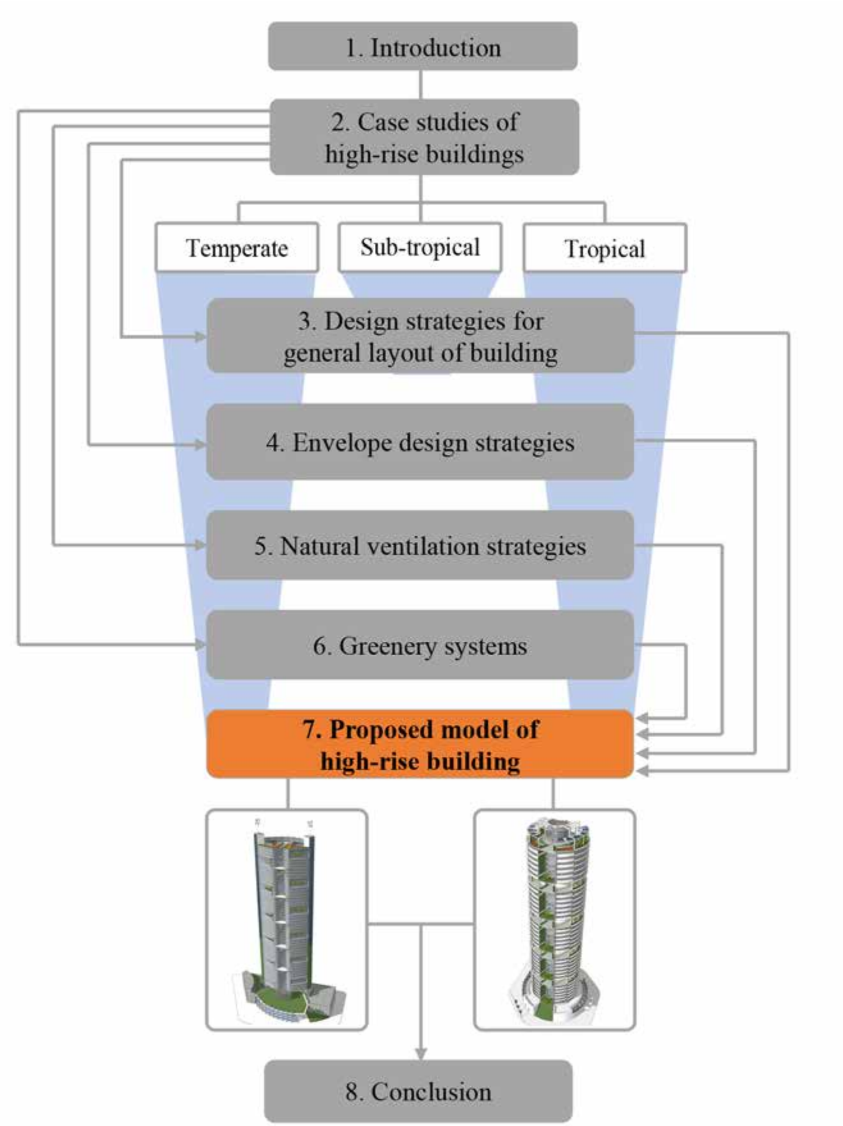
TOC


1. Introduction
2. Case studies of high-rise buildings
Temperate
Sub-tropical
Tropical
3. Design strategies for general layout of building
4. Envelope design strategies
5. Natural ventilation strategies
6. Greenery systems
7. Proposed model of high-rise building
8. Conclusion

7 Proposed model of high-rise building

The impact of architectural design strategies – geometric factors, envelope strategies, natural ventilation and greenery systems – for improving the performance of tall office buildings was investigated in the previous chapters. The results indicated the importance of architectural design strategies for improving the energy-efficiency of and thermal comfort in high-rise buildings. Some strategies were found to have larger impact. Knowing that the share of cooling and ventilation loads from the total end-use of energy in tall office buildings is huge, it can be inferred that the role of natural ventilation is of great importance for the energy-efficiency of tall buildings. Other factors such as shading in tropical climates, building orientation in sub-tropical climates, and infiltration and insulation in temperate climates had a higher degree of influence on energy consumption in tall office buildings. Furthermore, the energy impact of greenery systems was found to be insignificant; however, the environmental value that such strategies offer could justify their application.

Chapter 7 will consolidate the findings from previous chapters to point out climate specific design strategies that are required for energy-efficiency of tall office buildings in temperate and tropical climates. The outcomes will be used later by the end of this chapter to illustrate a proposed model of an energy-efficient high-rise office building for each of the investigated climates. A general conclusion is provided at the end of this chapter.

§ 7.1 Introduction

Rising fuel prices and taxation bands relative to building emission rates are stimulating building owners more than ever to invest on green building design and technologies (Gonçalves, 2010). As a result, designers are being requested to deliver more energy-efficient buildings to minimise dependency on fossil fuels and to reduce carbon footprints of their projects. However, achieving these goals requires a holistic approach. The approach to energy-efficient design can be summarized in four steps (Gonçalves, 2010) as can be seen in Figure 7.1. In order to have high-performance tall buildings, first there is a need to reduce the building’s demand for energy and the most straightforward approach is to design them in a way that reduces their appetite for energy. The second step involves reusing waste energy. “Reclaiming a significant proportion of this normally wasted energy is relatively straightforward, proven technology is widely available, and such reclamation can be economically beneficial in the long term" (Gilchrist et al., 2013, p. 157). Ventilation heat recovery systems, heat pumps, and combined heat and power (CHP) systems are few examples of waste energy reclamation. The third step is related to the use of energy-efficient indoor environmental control systems and new technologies. Finally, step four involves the application of renewable energy sources. The main focus of this research is to establish energy-efficiency for high-rise buildings through architectural design strategies.

FIGURE 7.1 The four steps of energy-saving in buildings. Adapted from (Gonçalves, 2010).

§ 7.2 Essential sustainability features for tall office buildings

§ 7.2.1 Building layout

The general layout of a building is of great importance for minimising the energy loads and for enabling passive design strategies. Form and orientation must reduce the energy use for cooling in summer and heating in winter, maximize the access to natural ventilation and daylight, provide unblocked views out from workplaces, while maintain a high percentage of usable space (see Figure 7.2). The larger the surface area of the envelope, the higher the heat gains and losses through the building skin. As a result, compact shapes are more desirable for reducing the energy use for heating and cooling in conditioned buildings. In mechanically ventilated buildings, an elongated shape may increase the energy use for fans due to higher pressure drops. In contrast, in naturally-ventilated buildings, the plan shape should be elongated for a more effective use of (natural daylight and) ventilation. The percentage of office areas that can be accommodated along the building perimeter increases when having a narrower plan shape, so that the energy use for electric lighting reduces. Furthermore, it is easier to distribute fresh air to all areas of a narrow-plan building using natural ventilation. Depending on the climatic conditions and the desire for employing natural ventilation, savings achieved by electrical loads and ventilation may compensate for the extra HVAC energy demand. In regards to space efficiency of the conventional air-conditioned tall buildings, a compact shape with a central service core has a higher percentage of usable space than elongated shapes with longer circulation routes and multiple cores. Furthermore, a narrow plan shape reduces the provision of large vertical spaces such as atria and sky gardens which are essential elements for providing natural ventilation and daylight in deep plan buildings with compact forms. Therefore, for a naturally ventilated building, a narrow plan shape might result in a higher percentage of usable space than a compact form.

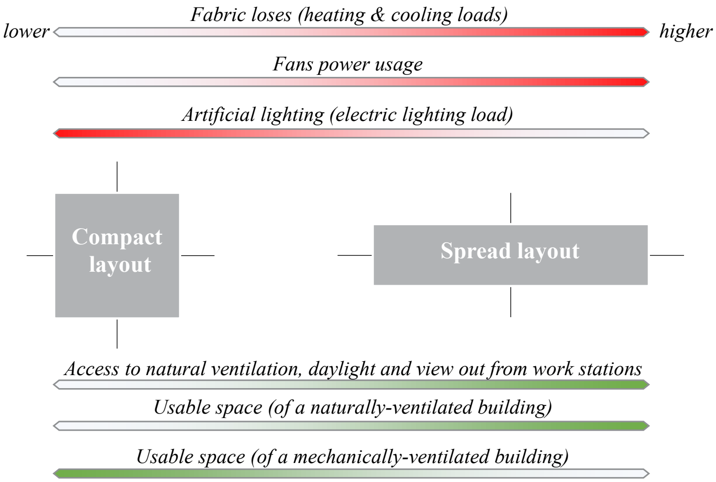


FIGURE 7.2 A comparison between the performance of compact and spread layouts.

Building orientation should be selected carefully, by taking into account the overall influence of the local climatic conditions (sun path and wind direction), zoning regulations, urban plan, and surrounding towers (see Figure 7.3). Occasionally, site limitations or contradictory design objectives (to make best use of sunlight and prevailing wind at the same time) do not allow to use the optimal shape and orientation for the building through the conventional way. Therefore, more innovative design options might be required to compensate for the effect of those limitations. For example, when wind and buoyancy-driven forces are employed together (via stepping sky gardens connected by a central atrium), there is greater flexibility with building orientation with regard to the prevailing wind direction. The building orientation should be able to maximize wind-induced ventilation by orientating the longer façades of a building perpendicular to the summer winds and buffer the building against cold winter winds. For temperate climates, avoiding shade from other tall buildings in an intensive urban environment is required in order to provide full exposure to the winter sun. However, in tropical climates, tall buildings can be leveraged from shading by surrounding buildings to reduce the amount of solar radiation on the building envelope.

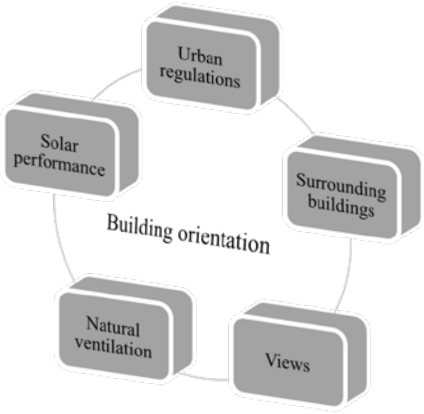


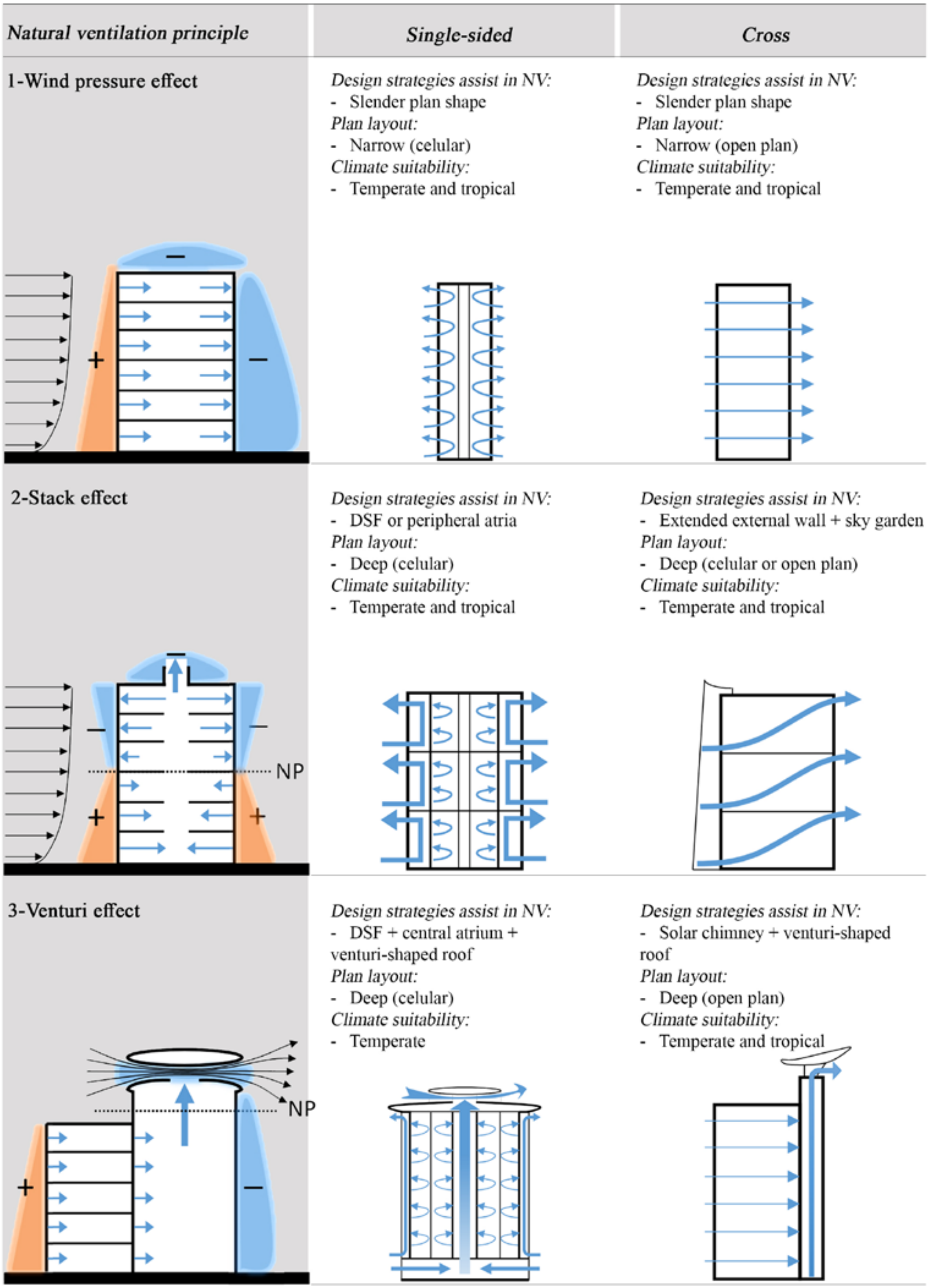
FIGURE 7.3 Parameters affecting the building orientation.

§ 7.2.2 Natural ventilation

Recent studies show that fans and space cooling together account for roughly 38% (in temperate climates) to 56% (in tropical climates) of the total energy use in multi-storey office buildings depending on the climate and other factors (Raji et al., 2017). Natural ventilation can therefore play a key role in maintaining thermal comfort and providing fresh air for tall office buildings. Pure natural ventilation systems ideally require no energy for the supply of fresh air since the major forces driving natural ventilation are wind and buoyancy. However, the effectiveness and duration of natural ventilation are usually affected by climate conditions.

Natural ventilation can be employed in different ways in tall buildings, depending on the primary purpose for using natural ventilation, the plan layout of the building and the suitability of a certain ventilation strategy for a particular climate. A graphical illustration of the most common natural ventilation strategies for high-rise buildings is presented in Figure 7.4. In order to extend the time period in which natural ventilation is effective, a ventilation strategy should be able to perform under different wind conditions and outdoor temperatures. On a windy day, pressure differentials generated by wind are the dominating driving force. A single-sided ventilation strategy can be effective as long as the room depth does not exceed approximately 2.5 times its height. For effective cross-ventilation, this ratio must be lower than around 5 (Wood & Salib, 2013). On a calm day with no wind, thermal buoyancy is the dominating driving force for natural ventilation. The buoyancy effect can improve the effectiveness of cross-ventilation when the ventilated spaces are facing a vertical shaft such as an atrium, a solar chimney, or a vertically continuous DSF structure. In winter, the DSFs, sky gardens, or peripheral atria can act as solar collectors and thermal buffers, preheating the cool fresh air before it enters the office spaces. In summer, natural ventilation can be provided through larger openings to ensure indoor thermal comfort conditions. Another effective strategy for producing a driving force for ventilation is using the Venturi effect by adding an element to the roof. It is a disk-shaped aerodynamic structure that should be positioned at certain height above the roof. In tall buildings, it is usually being incorporated over the exhaust opening of a multi-story DSF, solar chimney or atrium to increase the flow speed and prevent the risk of down flows. When the wind passes through the roof contraction (the narrowest roof section) the flow speed increases. This will provide significant negative pressure at the intended exhaust opening which improves natural ventilation of the building through a phenomenon that is called the Venturi effect (van Hooff et al., 2011).

TOC



Natural ventilation principle	*Single-sided*	*Cross*
1-Wind pressure effect	*Design strategies assist in NV:* - Slender plan shape *Plan layout:* - Narrow (celular) *Climate suitability:* - Temperate and tropical	*Design strategies assist in NV:* - Slender plan shape *Plan layout:* - Narrow (open plan) *Climate suitability:* - Temperate and tropical
2-Stack effect	*Design strategies assist in NV:* - DSF or peripheral atria *Plan layout:* - Deep (celular) *Climate suitability:* - Temperate and tropical	*Design strategies assist in NV:* - Extended external wall + sky garden *Plan layout:* - Deep (celular or open plan) *Climate suitability:* - Temperate and tropical
3-Venturi effect	*Design strategies assist in NV:* - DSF + central atrium + venturi-shaped roof *Plan layout:* - Deep (celular) *Climate suitability:* - Temperate	*Design strategies assist in NV:* - Solar chimney + venturi-shaped roof *Plan layout:* - Deep (open plan) *Climate suitability:* - Temperate and tropical

FIGURE 7.4 Different methods of employing natural ventilation in high-rise office buildings. NP=neutral point.

Occasionally, natural ventilation (both supply and exhaust without mechanical means) may be perceived to be inadequate, especially with large commercial buildings and, therefore, a hybrid ventilation system is a way of reducing the risk. Hybrid ventilation solutions, also known as mixed-mode systems, use a combination of natural and mechanical ventilation in order to minimise energy consumption. Typically, using natural ventilation when the external conditions such as air temperature or wind speed are optimal, and switching to mechanical ventilation when the external conditions do not allow natural ventilation.

§ 7.2.2.1 The impact of building form on natural ventilation

The magnitude of the wind pressure across the envelope of a building is primarily influenced by the building's form, the details of the façade (like protrusions), the velocity and direction of the wind, and the effect of the surrounding terrain. An aerodynamic form encourages the flow of wind around the external envelope and into the building (see Figure 7.5). This also reduces turbulence around the building and improves pedestrian comfort at street level; or the vortex effect might be amplified by using slender rectilinear building shapes in hot and humid climates where high wind speeds (with a certain upper limit) at the street level could be of assistance for improving the thermal comfort of pedestrians. Curved or funnel-shaped structures can be used to lead the wind (desired or unwanted) in particular directions (into or away from the building). Another effective strategy to capture wind from a wide range of directions is through the outward extension of walls (wind wing walls) when the site limitations do not allow to orient the building along the prevailing wind axes.

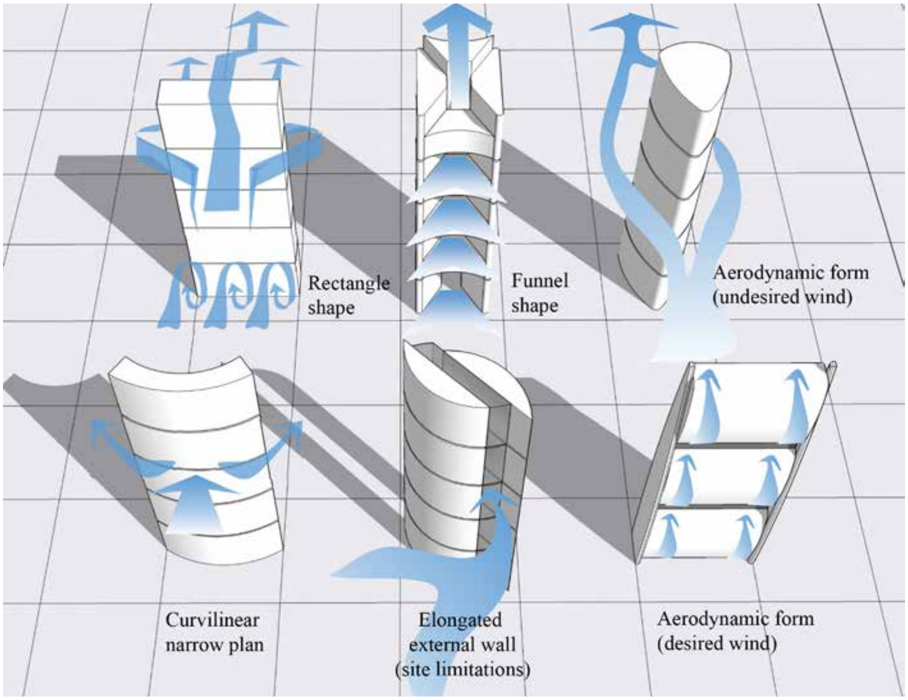


FIGURE 7.5 Building form for effective natural ventilation.

§ 7.2.3 Natural daylight

The value of daylight has widely been acknowledged due to its direct impact on well-being, productivity and the overall quality of a building's internal space. In an office building, occupancy is during the day and the access to daylight is of great importance. Plan shape and interior layout can highly influence electric lighting loads. The energy demand for electric lighting reduces when the percentage of peripheral offices along the external façade becomes higher. Current practice suggests for ideal daylighting access in cellular office buildings to limit the plan depth to no more than 6–8 m from a window (Wood & Salib, 2013), or around double this amount if light comes from two sides. When the use of compact layouts is a key factor for energy saving, other elements such as atria, sky gardens and transparent partitions can be employed to enhance natural light penetration. Temporarily used spaces like meeting rooms can be placed in the deeper parts of the floor plan to let permanent work stations be lit naturally. Furthermore, higher values of the WWR along with selecting a glazing type that features a high light transmission value are highly desired for reducing the electric lighting loads. However, improving the access to daylight should not lead to glare discomfort, excessive use of sun shades and overheating. These often conflicting factors should therefore be carefully balanced to ensure that energy saving targets can be achieved while at the same time having a comfortable indoor environment. Last but not least, new fixtures, and occupancy and dimming control systems can provide the building with significant amounts of energy saving for electric lighting.

§ 7.2.4 Atria and voids

An atrium is a multifunctional architectural element that can be integrated into the design of tall buildings in order to assist natural ventilation and create day-lit spaces with pleasant views in deep-plan buildings (see Figure 7.6). Wind-induced ventilation might not be able to elevate indoor velocity within low wind speeds or for buildings with a deep floor plan. In such a case, a natural ventilation strategy that employs atria performs better due to the combined effect of wind and buoyancy forces (see chapter 5, part b). A careful orientation of an atrium in relation to the sun significantly improves the effectiveness of natural ventilation. For the buoyancy to perform well, there is a need to create large temperature difference along the atrium height by capturing sunlight and by internal gains; this also works particularly well in case the outdoor air temperature is far below the indoor air temperature. At milder outdoor temperatures, such as in a sub-tropical climate, external open voids can be incorporated in tall building design to provide the inward-facing offices with access to daylight and fresh air and increase the indoor air velocity. The application of open voids is not recommended in temperate and tropical climates, as the increased envelope surface area might increase the energy need for cooling and/or heating.

When the outdoor temperature is below the lower limit of the comfort temperature boundary, tempered air from an atrium can extend the time period in which natural ventilation is effective as compared to when fresh air is directly brought to the inside of the offices. In this regard, a peripheral position of the atria is more favourable to bring the tempered fresh air from a different range of directions into peripheral offices, but a central positioning will help to bring natural daylight and ventilation deeper into the plan. When using a full-height atrium, there is a risk of high temperature differences between bottom and top floors and extreme stack effects and drafts. In order to control this excessive stack effect, a full-height atrium is usually segmented into smaller zones with lower pressure differences. Segmenting an atrium can also minimize the variation of the fresh air entry rate on different floors. Furthermore, segmenting an atrium provides acoustic insulation for the occupants of a multi-tenant building. Vertical circulation shafts such as an escalator voids can act as extraction shafts by utilizing the stack effect in the void. However, in such a case high air speeds and temperature differences need to be avoided.

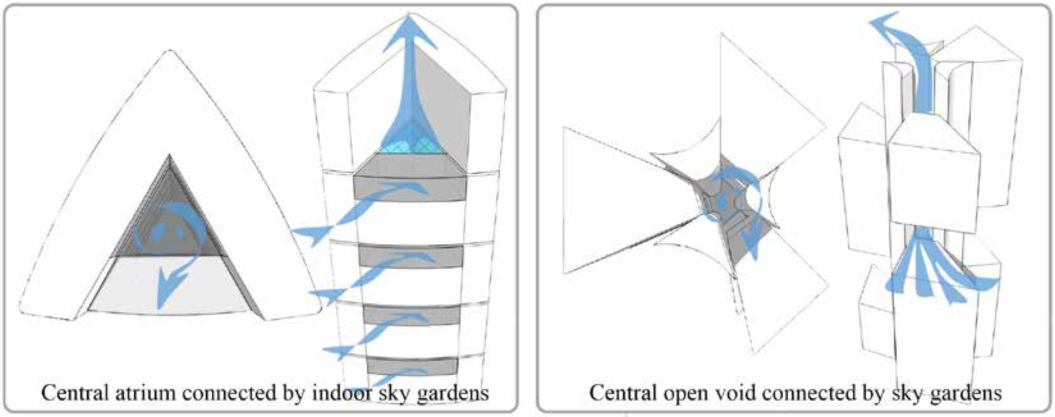


FIGURE 7.6 The use of atrium or open void to assist natural ventilation and create day-lit spaces. The above building shapes are adapted from the Commerzbank (left) and Cube Tower (right) in temperate and sub-tropical climates respectively.

§ 7.2.5 Indoor sky gardens (sky courts)

Indoor sky gardens are enclosed spaces with usually more than one storey height that moderate between external and internal environments. They can be integrated in building design – especially in combination with an atrium – to take in the fresh air and/or extract the stale air, light the space, and provide a greater sense of community within a tall building. Adding greenery to the sky garden has cooling benefits for the indoor environment (more effective for areas in the vicinity of vegetation) due to evapotranspiration and they can improve thermal comfort levels. Indoor greenery also contributes to the purification of indoor air through bio-filtration.

§ 7.2.6 Solar chimney

Solar chimneys are increasingly incorporated into the design of high-rise buildings to assist ventilation in a wide range of climates. A solar chimney is a passive ventilation system that uses solar heat to increase the stack effect and thereby displace warm interior air with cool exterior air. In theory, the hot air rises through the chimney structure and pulls the air from inside the building into and through the chimney shaft and then exits the building from the opening at the top (see Figure 7.7). In order to induce adequate thermal buoyancy within the solar chimney, the external leaf needs to be fully-glazed, the interior leaf should be heat absorbing (dark), and it requires a suited orientation to capture more radiation. A high thermal mass of the interior leaf ensures that the chimney will be active during a longer period of the day. Unless the solar chimney is designed entirely around this principle, it is not effective. According to chapter 5, for a building that has a narrow plan layout (EWI building), a buoyancy-driven ventilation by using solar chimney was not more efficient than other ventilation strategies. In contrast, for buildings with a deep plan, cross-ventilation can hardly occur, so that buildings require vertical shafts such as an atrium or solar chimney to facilitate natural ventilation (Wood & Salib, 2013). The occurrence of a reverse flow (under no sun conditions with higher outdoor than indoor air temperatures) could lead to heat penetration into the building, which is not desirable for ventilation. A wing roof that is directly located over the exhaust opening can enhance the air flow through the Venturi effect and prevent the risk of down flows regardless of the wind direction. Furthermore, increasing the height of the chimney structure can increase the extent of pressure gradients along the shaft, hence increase the suction.

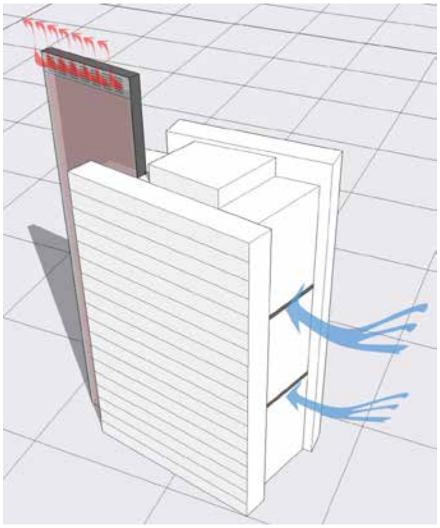
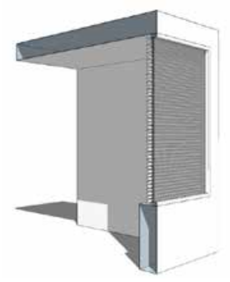
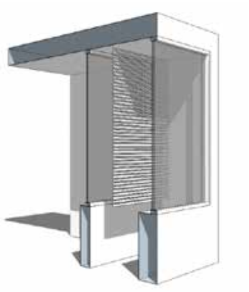
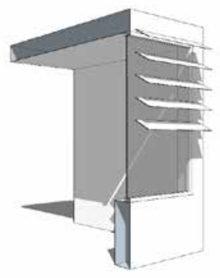


FIGURE 7.7 The application of solar chimney for air extraction in tall buildings. The above model is adopted from Manitoba Hydro Place in Winnipeg (cold climate).

§ 7.2.7 Sun shading

Shading is a key environmental control strategy to maintain thermal comfort inside the building and to reduce the energy consumption, especially in buildings with a large window-to-wall ratio. The importance of reducing (undesired) external thermal loads on vertical surfaces is even higher for the high-rise typology as they are more exposed to solar radiation and the extent of internal gains are higher compared to the low-rise typology with an equivalent floor area. Shading can be achieved by a wide range of building components including interior or exterior elements such as blinds, louvers, overhangs, side fins, and balconies. Other ways to control sunlight without using blinds or external shading devices are the application of greenery systems, electrochromic glazing, façade-mounted PVs, self-shading facades (e.g. double-skin façade) or particular building forms. Each of these strategies have their own pros and cons as can be seen in Table 7.1. The information presented in this table are collected from comparative studies on twelve case buildings in chapter 2, results of energy simulations in chapter 4, and a literature review on greenery systems in chapter 6. All in all, sun-shading devices should neither affect the view out of the windows nor substantially reduce the daylight and desired solar heat gain.

SHADING STRATEGY	Benefits and drawbacks	
Manually operated or motorized venetian blinds inside the building		✓ Contribute effectively for glare control ✓ Lower installation and maintenance costs ✗ Ineffective at reducing the cooling loads ✗ Limit the access to outside views when they cover the entire window
Motorized blinds integrated in the intermediate space of a double-skin façade		✓ The outer skin of the double-skin façade provides an effective shield for blinds against rain, dust and wind; hence result in less maintenance ✓ More effective than indoor blinds at limiting the amount of heat radiated into the interior space ✓ The most viable option when the incorporation of exterior shading devices might cost a lot or is not safe ✗ It may cause overheating if there is no proper ventilation within the two layers of the building façade so they are less efficient than the external shadings for reducing the cooling load ✗ Limit the access to outside views when they cover the entire window
Motorized venetian blinds on the external façade		✓ Blades can be set at different angles so that a very effective strategy for blocking low sun from entering east- or west-facing windows ✗ Can only be operated at wind speeds of lower than 10-15 m/s ✗ Prone to damage by rain, dust and wind ✗ Less viable solution for tall buildings due to impended cleaning access and wind noise ✗ Limit the access to outside views when they cover the entire window
Fixed louvers		✓ Very effective at blocking low sun from entering east- or west-facing windows ✗ For heating-dominant climates in which passive heat gains are highly desired, louvers can increase the heating demand of the building in the winter; hence their application should be avoided on the south-facing windows (in the Northern Hemisphere) and on the north-facing windows (in the Southern Hemisphere)

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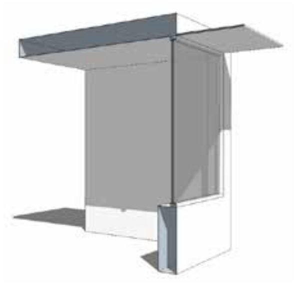
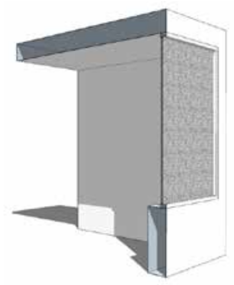
TOC

SHADING STRATEGY	Benefits and drawbacks	
Overhang (fixed)		✓ Very effective at shading high sun angles in the summer, in particular for windows facing towards: – South on the Northern Hemisphere – South and north on the equator – North on the Southern Hemisphere ✗ Ineffective at blocking low sun angles (not suitable for east- and west-facing windows) ✗ They are not an economical and aesthetically pleasing solution for high-rise buildings
Side fins (fixed)		✓ Effective for blocking sun from a south-easterly or south-westerly direction ✗ It can limit a panoramic view
Smart glass (electrochromic glazing)		✓ Allows for uninterrupted views ✗ In their darken state, the increased heating (winter) and electric lighting loads might offset the cooling effect ✗ Not as effective as external shading devices to keep the solar radiation/heat from entering the building, especially in tropical climates with high amount of solar radiation
Façade-mounted solar PV		✓ Facades (and roof) of high-rise buildings offer a great opportunity for PV to provide shading and generate electricity ✗ Using PV on the facade has less output compared with using it on the roof

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TOC

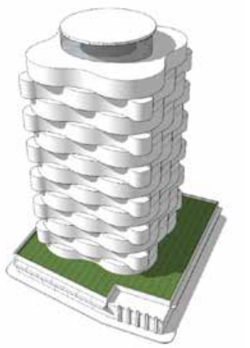
SHADING STRATEGY	Benefits and drawbacks	
Recessed or projected balconies combined with greenery systems		✓ In tropical climates, recessed balconies are good strategies for providing deep permanent shading on the east and west sides when larger openings are needed to get access to daylight or natural ventilation ✓ Shading and evapotranspiration from implementing vegetation on balconies, sky gardens, roof or vertical greening can regulate the microclimate environment around and inside the building. However, in temperate climates attention should be paid to avoid shading the facade where passive solar gain is desired ✗ The effect of heat transfer through the increased surface by recessed terraces might offset the shading effect
Self-shading façade		✓ Provide shading without blocking the views ✗ The effect of heat transfer through the increased surface might offset the shading effect

TABLE 7.1 The suitability of different shading strategies for high-rises.

External shading is more favourable in hot climates with a high amount of solar radiation. When there is a need for a better sunlight control system, an adjustable shading would be a better option. However, a considerable amount of maintenance and repair is usually required by using external operable shading devices, which needs to be accounted for in a life-cycle cost analysis of their use. In some locations, hazards such as high winds, nesting birds or earthquakes may reduce the viability of incorporating exterior shading devices in the design. Venetian blinds are the most commonly used shading systems in temperate climates. However, typical venetian blinds can only be operated at wind speeds of lower than 10 m/s (or 15 m/s under specific conditions) (Sobek et al., 2013). For this reason, they are often being employed either inside of the building or within the protected air gap when using a double-skin façade, while the latter is a better option in terms of energy saving.

TOC

§ 7.2.8 Greenery systems

The most common places in a building that can be used to accommodate vegetation are roof greening, vertical greening, terrace planting and indoor plants in interior spaces such as sky gardens. Climate conditions and the excessive height of high-rises may limit the application of greening systems to specific areas in the building. The most common greenery strategies for tall buildings in temperate climates are those that are protected against outdoor conditions by placing them inside the building such as indoor sky gardens. In tropical climates, where the outdoor conditions are more favourable for the growth of plants, outdoor greening strategies can be employed on the roof or over the façade. Greenery concepts can offer many benefits to a building. Among them, energy saving is the most investigated one. The energy saving through application of greenery systems comes from three phenomena by plants or their substrate. While evapotranspiration and shading contribute in the reduction of cooling load, the insulation effect of greenery systems is very limited. In winter, roof greenery may even lead to slightly higher heating loads (due to a small amount of evapotranspiration). The maximum efficacy of greenery systems is during summer. Furthermore, on sunny days or in places with higher solar radiation, the efficiency of greenery systems is higher. The extent of energy saving from the application of greenery systems, however, is highly influenced by the building's envelope properties. As shown in chapter 4, adding a 10 cm green roof to a well-insulated roof hardly influenced energy consumption in both temperate and tropical climates.

However, other large-scale benefits on UHI, air pollution or rainwater management could justify the application of greenery systems. Through photosynthesis plants take up carbon dioxide from the air and release oxygen. CO_2 emission is the main driver of global climate change. This is an unavoidable consequence of the use of fossil fuels. A study by the University of Dresden showed that one square meter of a façade that is covered by ivy plant can absorb around 2.3 kg of carbon dioxide from the atmosphere per year (Ottelé, 2015). The vast vertical surface area of a high-rise building is a good platform to apply vegetation. If greenery systems are broadly integrated into tall buildings, they can mitigate the CO_2 concentration on urban sites and reduce the buildings' share of carbon dioxide emission that comes from energy consumption.

§ 7.3 Design guidelines for tall buildings in a temperate climate

§ 7.3.1 Building form

The results of the total annual energy consumption for 12 floor plan geometries with the same climatically conditioned floor area but different ratio of surface area to volume (in chapter 3) showed that compact forms could result in more energy saving in temperate climates (see Figure 7.8). Among compact forms, a high-rise building model with an oval form has the lowest total energy use. A relatively higher energy efficiency of the ellipse shape is caused by three geometry-related parameters. It has a high degree of relative compactness which is highly desired for reducing the amount of gains and losses through the building skin. Furthermore, it has a relatively lower plan depth, which reduces the electric lighting demand in comparison with other compact forms. Finally, the extended sides can be oriented environmentally to utilize passive heat gain in winter and reduce overheating from the east or west orientations in summer. This degree of efficiency is regardless of the benefits that this form can have for naturally ventilated buildings. The aerodynamic form encourages the flow of wind around the external envelope and into the building from a wide range of directions. This also reduces turbulence around the building and improves pedestrian comfort at street level. Moreover, curvilinear shapes can provide a panoramic view to outside and improve the aesthetic qualities of the design.

TOC

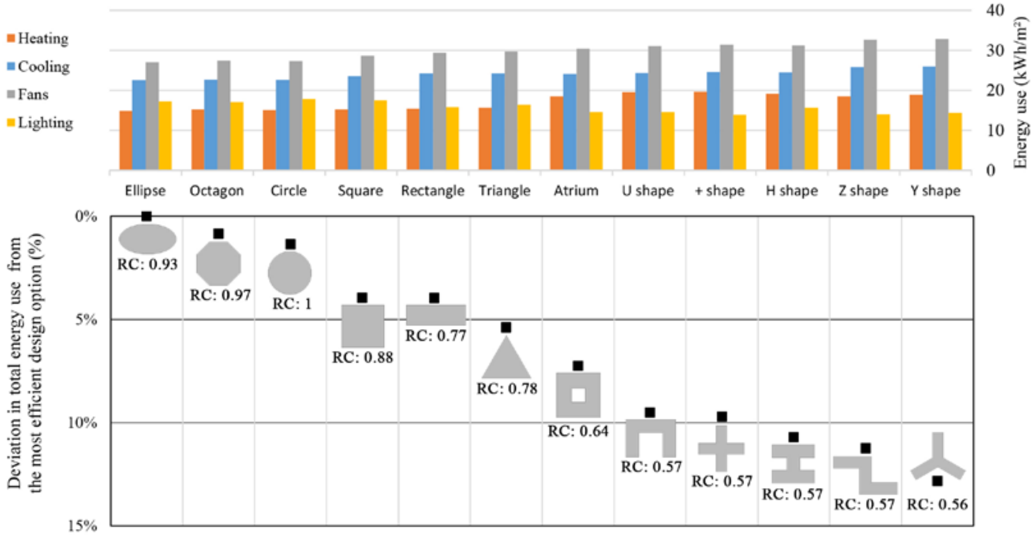


FIGURE 7.8 The maximum deviation of total energy use from the optimal solution for different plan shapes and their breakdown of total energy use.

The results were obtained from a building model that features a single-skin façade with a window-to-wall ratio of 50%, relatively high insulation values for the envelope (U values for windows and walls were 1.50 W/m^{2}K and 0.35 W/m^{2}K respectively), while indoor blinds were adjusted only for glare control. Since the investigated building model was featured by indoor blinds, an integration of a high-performance shading strategy might reduce the deviation in total energy use among different plan geometries.

The thermal resistance of the building envelope is another influential factor in determining the optimal shape of a building. The impact of a building's form on its energy consumption is higher for buildings with a low-performance façade. As a result, when a building has a lower U-value for glazing and external walls, compact shapes can reduce the excessive gains and losses through the building envelope. To put it another way, a high thermal resistance of the envelope is needed for buildings with a spread layout in order to reduce the extra amount of heat gains and losses. Furthermore, a spread layout is more sensitive to a change in orientation, therefore, selecting an environmental orientation for the building is more critical for this layout of plan. While atria and sky gardens are essential elements for providing natural ventilation and daylight in deep plan buildings, the application of such elements will reduce the percentage of the usable space. When using a compact layout, the share of each cardinal direction from the envelope area would almost be equal (except the ellipse shape), therefore, the risk of overheating or glare discomfort for work stations located at close distance from east or west orientations would be higher so that more attention should be paid to the selection of envelope measures (glazing type, WWR, and shading system) for the easterly- and westerly-positioned facades with the use of a compact shape.

§ 7.3.2 Building orientation

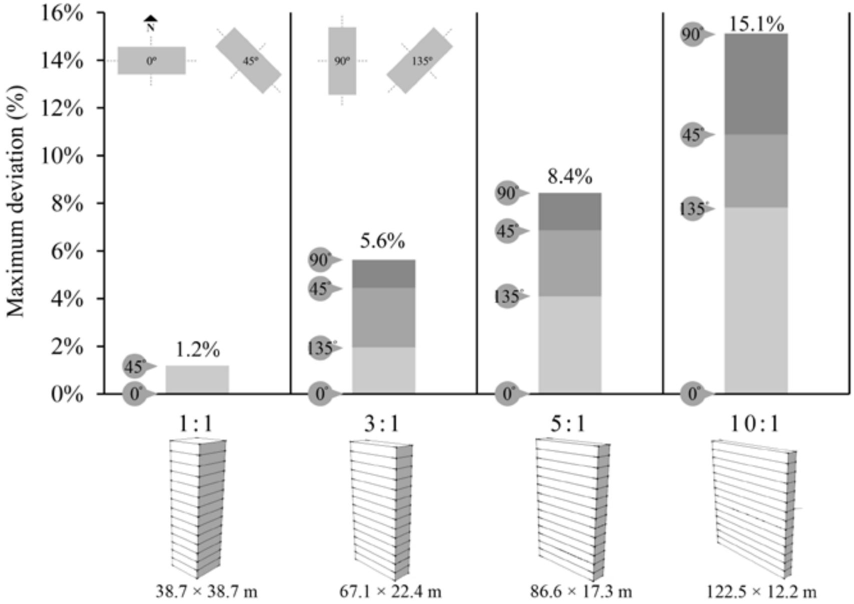


FIGURE 7.9 The percentile difference in the total energy use between the most and least efficient orientation for different plan layouts in temperate climate.

The impact of building orientation on the total energy use is highly influenced by the plan layouts of the building and the climate conditions of the site. Generally, compact forms (deep plan buildings) are less sensitive to a change in orientation than spread layouts (see Figure 7.9). The reason is that a compact shape has less surface-to-volume ratio and therefore the extent of heat exchanges (via conduction or air infiltration), between the inside (conditioned space) and the outside (unconditioned space) of the building is less. Moreover, the impact of a change in orientation on total energy use is more dominant in a temperate climate than in a tropical climate and therefore a higher

TOC

consideration should be given to the orientation of buildings in temperate climates. In case of a compact plan layout (1:1), the maximum deviation in total energy use between the most and least efficient orientations is 1.2%, while these differences can rise to a peak at around 15.1% for very narrow plan layouts (10:1).

The thermal loads of a square-shaped building reached its minimum value when facades are directly oriented toward the four cardinal directions. For narrow plan layouts, a wrong decision regarding the building orientation can result in a tremendous increase in energy consumption. The result shows up to 15.1% increase in total energy use with the application of a very narrow plan layout (10:1) that is oriented north-south. In order to achieve the maximum efficiency by using a spread layout, the long axis of the building should be extended along the east-west axis. In addition, a 90° rotation from the north is the least efficient orientation for all plan aspect ratios with an equiangular four-sided plan shape.

§ 7.3.3 Natural ventilation

The wind speed increases with height and this is the most critical factor when considering natural ventilation in high-rise buildings. The pressure gradients around the facades of a high-rise building can be very high (up to 30 Pa) (Sobek et al., 2013). This effect is more dominant in temperate climates as the average and maximum wind speed is commonly higher. This makes it almost impossible to open a window on the periods of higher wind speeds. A common strategy allowing natural ventilation (even at high wind speeds) is the use of double-skin façades. Users can open the internal windows, while pressure differences are buffered by the external leaf. In temperate climates, a double-skin façade offers many advantages over a single-skin alternative with regards to user comfort. The effect of drafts induced by open windows is higher for a single-skin façade than a double-skin façade. The use of a single skin façade, as opposed to a double skin façade, allows fresh air to enter the building with minimal obstructions (this is an advantage for summer ventilation), so that the internal air temperature might drop below the comfort boundaries more often during the cooler periods due to a higher number of air changes per hour; hence increase the building’s reliance on mechanical ventilation and the energy use for heating. With appropriate strategies, natural ventilation can be further extended beyond the transitional seasons (see Figure 7.10). On cold days, solar gain in the double-skin cavity can serve to preheat fresh air before it enters the rooms. As a result, office rooms can utilise natural ventilation for a longer period. In order to extend the duration of natural ventilation for providing fresh air throughout the course of a year, it is recommended to distribute the tempered air from a thermal buffer space (such as atrium, double-skin façade, or sky garden) into the offices.

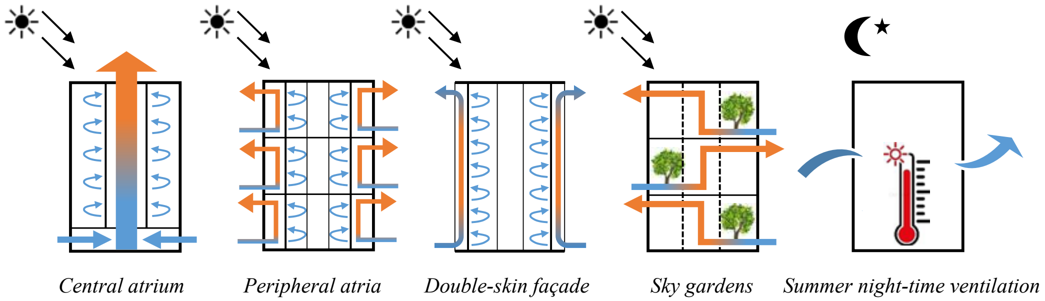


FIGURE 7.10 Ventilation strategies for increasing the duration of natural ventilation in temperate climates.

However, the design of double skin facades requires more consideration compared to conventional single skin façades. The internal configuration of the cavity in a DSF might increase the resistance of the air flow path, hence might reduce the air flow rate in comparison with a single-skin façade. Selecting an optimal combination of all influential parameters including the size and location of air vents, angle and position of blinds, and the structure of DSF itself (cavity depth and height) is required in order to reduce the resistance of the air flow path and provide an easier flow of air. In addition to that the double skin façade can easily get too warm or too cold. Therefore, in order to take the most advantage of it, it is necessary to adjust the operation of vents (air inlets and outlets) according to the variations of temperature inside and outside of the building. The minimum temperature by which natural ventilation is allowed is another major factor for maintaining thermal comfort within the ventilated spaces and therefore it should be carefully adjusted according to outdoor conditions and the comfort temperature boundaries for the naturally-ventilated buildings.

As chapter 5 showed, the percentage of occupancy hours in which active cooling is necessary to provide thermal comfort reduced to a range between 5-7% (average value for east and west facing offices respectively) during the summer months (May-September) for a properly ventilated double-skin façade system in the temperate climate. The simulated model in this case was a narrow plan building that had north-south orientation. This means that there might be no need for cooling in the temperate climates with the application of natural ventilation for a properly oriented building during the summer. In temperate climates where the diurnal temperature difference is high, buildings can take advantage of lower external air during the night to cool down the building fabric and remove the accumulated internal heat loads gained throughout the day. Buildings that have exposed thermal mass (such as exposed concrete slab structures) can better utilize night-time ventilation in summer.

TOC

§ 7.3.4 Façade type

Double-skin facades (DSFs) are becoming a vital ingredient of tall buildings' design due to the various advantages they offer for energy-saving and sustainability. They are currently the standard solution for high-rise buildings in temperate climates. The cavity space is a major contributor to the thermal behaviour of a double-skin façade. According to the form in which the cavity space is divided, four types of structure can be identified for a DSF: box (divided both horizontally and vertically), shaft (vertically continuous), corridor (horizontally continuous), and multi-storey (extended over several floors or the entire building) (Oesterle, 2001). For the box and corridor types, the height difference between the air openings is small, thus the stack buoyancy would be very limited. In order to create a stronger stack effect, it is better to extend the intermediate space over a number of stories or the entire building by using vertically continuous cavity spaces. These typologies require fewer openings on the external leaf which make them more appropriate solutions for dense urban sites where the external noise levels are high. However, the occupants on the upper floors of a DSF building that employs shaft or the multi-story cavity type might experience a higher number of discomfort hours due to the accumulation of heat at higher levels. An extension of double-skin façade over the roof can increase the airflow rate; hence reduce the accumulation of heat and high temperatures on the top floors. Another important issue in double skin facades that continue vertically over several floors, is the potential for fire or smoke spread; hence, sealable dampers are required between every level.

There is no need to employ external shading elements when using a double-skin façade; hence the associated cost and risk (e.g. regular cleaning and wind noise) that external shading would have for a tall building will be eliminated. When the solar radiation reaches a shading device, part of the heat is reflected back to the exterior by the shades and the rest will be absorbed by the outer leaf of façade or the shade itself. The heat absorption may increase the temperature within the double-skin façade if there is no proper ventilation within the two layers of the building façade. Therefore, particular attention has to paid to the constant ventilation of the air gap between the two layers of the building façade, otherwise there is a risk of overheating in the intermediate space and accordingly the increase of energy use for space cooling in summer. Finding an optimal configuration for the design of a DSF building is a complicated process that needs an in-depth analysis of heat transmissions, solar gains and air flow patterns to be carried out. In this regard, a large number of thermal simulations on the total energy use and different energy end-uses on a yearly base and CFD simulations for different wind and temperature conditions is required. The influential design parameters affecting the performance of a DSF system are: the position of blinds within the cavity, the slat angle of blinds, the reflectivity of slats, the operation of blinds, the depth of the cavity, the size and position of air inlets and outlets within a DSF, the glazing type, and the orientation of the façade, as shown in Figure 7.11.

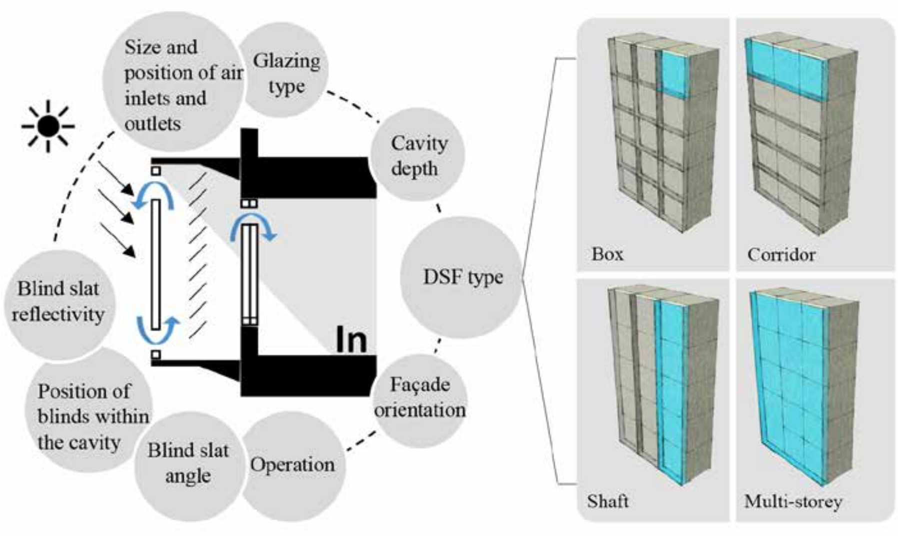


FIGURE 7.11 Parameters with major contribution to the thermal behaviour of a double-skin façade and the effectiveness of natural ventilation strategy.

§ 7.3.5 Shading

The outer skin of a double-skin façade act as a protecting layer against rain, dust and wind and allows to place the sunshades on the exterior of the (inner) building skin within the cavity space. The performance of indoor blinds within a DSF cavity can be improved significantly with the right selection from different options for slat angle, slat reflectivity, blind operation and its location within the cavity. The design recommendations for improving the performance of indoor blinds within a DSF cavity are provided in Figure 7.12.

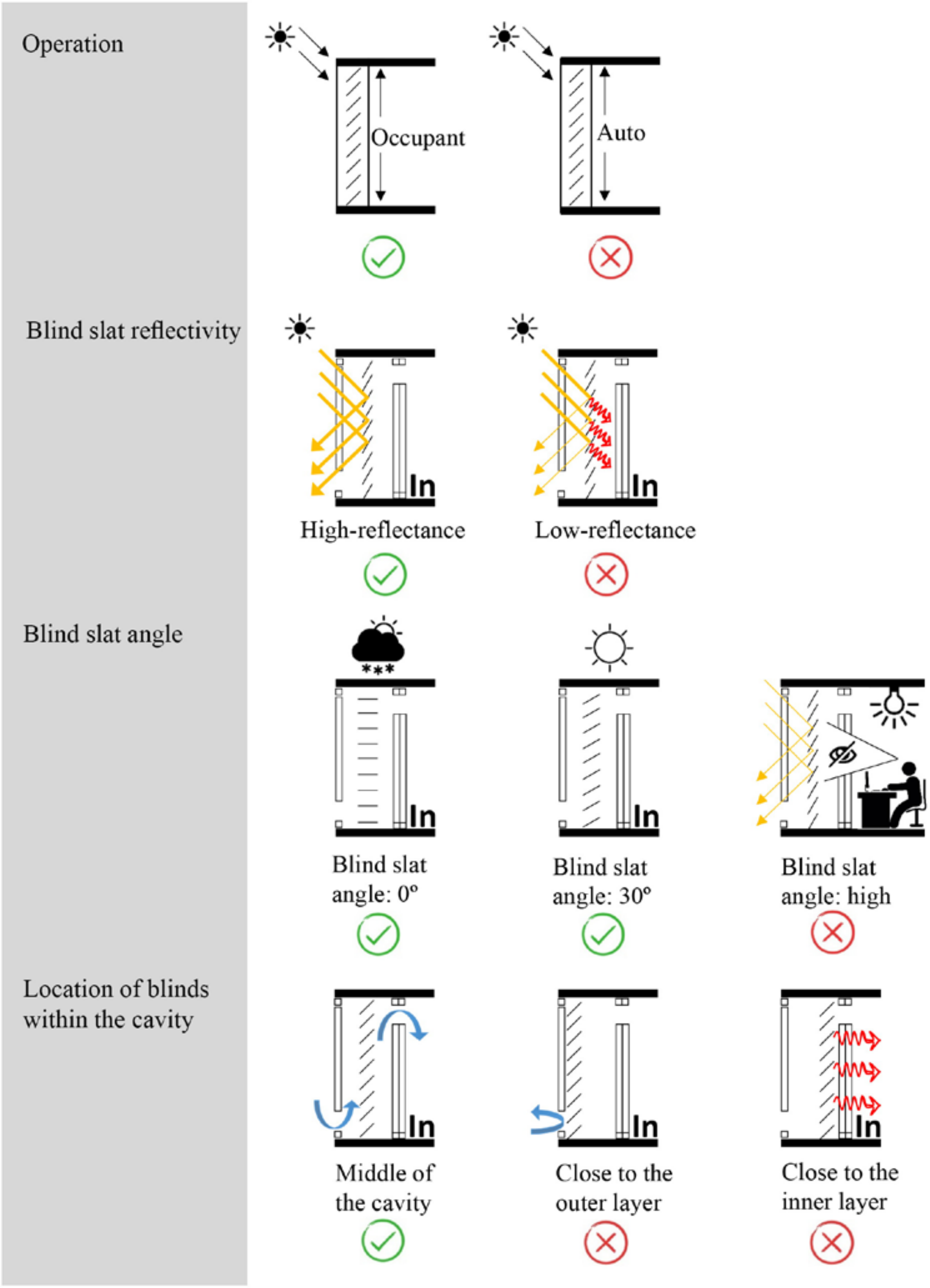


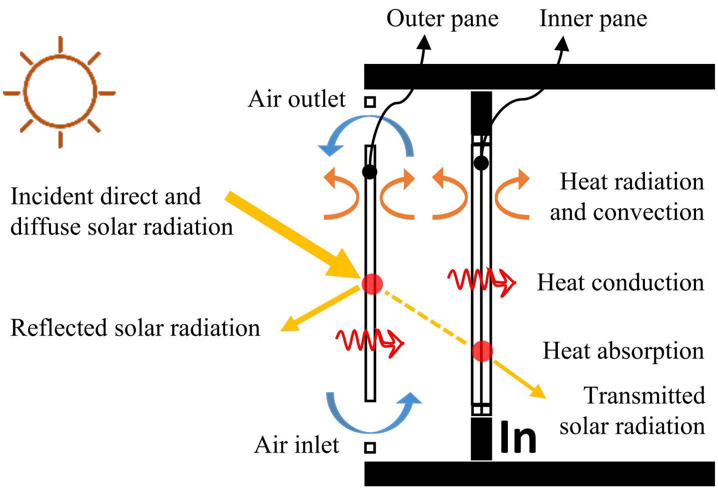
FIGURE 7.12 Design recommendations for improving the performance of indoor blinds within a DSF cavity.

The location of blinds within the cavity has significant influence on air temperature and airflow rate. Generally, blinds that are located in the middle of the cavity perform better in terms of solar heat gain control than those close to the inner layer. Placing the blinds close to the inner layer leads to higher heat transfer from the cavity into the room; hence higher cooling demand. When blinds are placed in the middle of the cavity, they not only provide shading but also enhance the air circulation on two sides (Gratia & De Herde, 2007). The effectiveness of solar shading devices depends also on how they are controlled. In cellular offices, it is important that occupants can override the BMS to ensure their individual comfort. Psychologically, occupants with more control over their environment are more tolerant to high or low temperatures (Nicol et al., 2012). The quality and amount of daylight, glare, natural ventilation and view can be set through different blind slat angles. In the winter, a blind slat angle of 0° will result in more energy saving in case there is no need for glare protection (Yun et al., 2014). However, in summer a blind slat angle of 30° is the optimal configuration for energy-saving and glare control (Yun et al., 2014). High slat angles can increase the lighting demand, prevent solar heat to enter the building in winter and block the views from work stations; therefore, they are not recommended.

The cavity depth is another parameter that can influence the thermal behaviour of a double-skin façade. The optimal depth of cavity on each orientation depends on the required amount of air changes and thermal insulation for the local site climate conditions. The surface temperature of DSF elements and solar heat gain in the cavity increase with shorter cavity depth. The cavity depth can also influence the air flow rate. The south façade receives higher direct sunlight than the north façade, therefore, the depth of the cavity in the south façade should be higher to reduce the excess heat. For the north-facing façade, however, the cavity depth might be reduced to improve the access of daylight.

§ 7.3.6 Glazing type

For temperate climates, the thermal transmission through a glass pane should be reduced by choosing a low U value glazing type. Furthermore, passive heat gains and daylight penetration are highly desired for reducing the heating and electric lighting loads, so high SHGC and Light Transmission value is required. The inner pane in air-conditioned DSF buildings is the place where the majority of heat transfer occurs due to higher temperature differences between the conditioned indoor space and unconditioned air in the cavity. Therefore, double-glazed pane with higher thermal insulation is better to be placed at the inner layer in order to reduce the radiative and convective heat transfer into the building, while single-glazed clear glass with Low emissivity (Low-e) coating can be applied at the outer layer to improve the buoyancy effect and airflow rate inside the DSF cavity (see Figure 7.13). Low-e coatings allow visible light to be transmitted while minimizing the amount of ultraviolet and infrared light that can pass through glass. In temperate climates with high heating degree days (HDDs), clear glass allows for relatively easy transmission of both heat and light into a building, thus reducing the energy that is typically required for heating and electric lighting by the application of tinted or reflective glasses. However, effective shading and ventilation strategies are essential with the use of a clear glass, otherwise it may lead to a significant amount of heat transfer from the cavity into the building and therefore higher cooling demand on summer days with clear skies.



Inner pane	Double-glazed solar control low-e coating (e2 = 0.1) clear 6 mm/13 mm Argon U-value: 1.50 W/m²-K SHGC: 0.57 Light transmission: 0.74
Outer pane	Single-glazed passive low-e coating (e2=0.2) clear 6mm U-value: 3.78 W/m²-K SHGC: 0.72 Light transmission: 0.81

FIGURE 7.13 Air flow and heat transfer within a DSF system, and the recommended glazing type.

§ 7.3.7 Window-to-wall ratio (WWR)

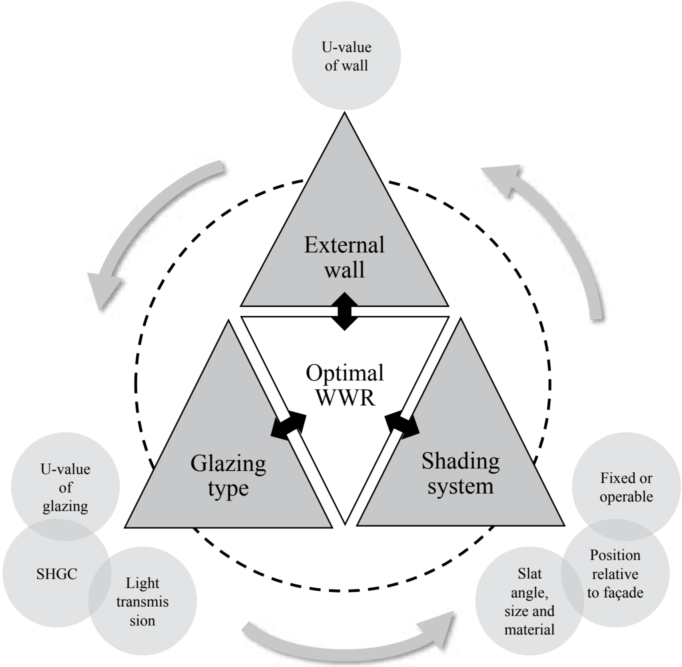


FIGURE 7.14 Envelope parameters with the highest impact on its thermal resistance.

As shown in Figure 7.14, the optimal WWR value depends on several factors such as the building's envelope properties (U values of windows and walls) and the incorporated solar shading strategy, as well as the internal plan layout. Therefore, the optimal values might vary to some extent among different building designs and site locations. The higher the thermal resistance of the envelope is, the lower the impact of WWR on total energy use is (see Figure 7.15); therefore, the building can take advantage of larger windows to maximize the access to daylight and views out. These are the two important parameters affecting the occupants' well-being and productivity, in particular for a high-rise building design.

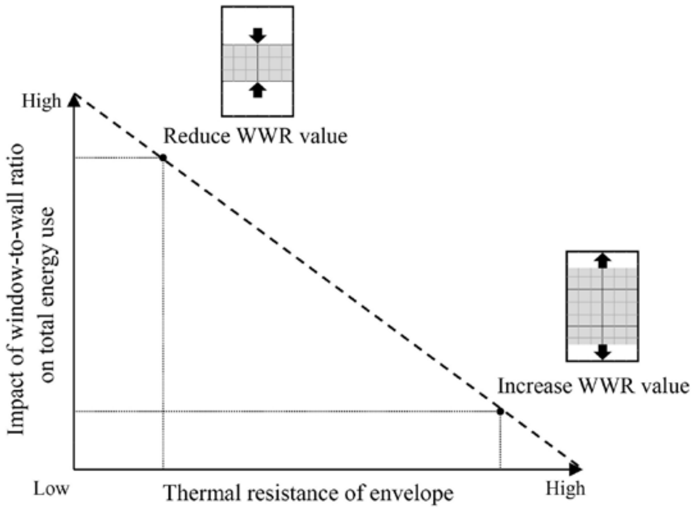


FIGURE 7.15 The relationship between thermal resistance of the envelope and the impact of WWR on total energy use for the selection of the optimal WWR value.

As chapter 3 showed, particular window orientations had greater sensitivity to a change in the WWR value. The sensitivity of different window orientations can be defined by calculating the maximum deviation of total energy from the optimal WWR value. In this regard, the west-facing and east-facing windows are the first and second most sensitive orientations respectively. Therefore, the east- and west-facing walls should avoid high WWR values, especially in the absence of sun shading control system. The north-facing façade is the least sensitive orientation, with no significant variation in energy use when relatively high insulation values (U value: 1.50 W/m^{2}K) are included for windows. So that the ideal WWR for north-orientated windows can be found in a considerably wider range (10–90%). The sensitivity of south-oriented windows is highly dependent on plan depth. A wrong decision regarding the WWR value for the south-facing façade of a narrow floor plan can cause a greater increase of the cooling energy use than of a deep plan building. The recommended values along with the sensitivity of different window orientations to a change in the WWR value is provided in Figures 7.16a and 7.16b. It is important to note that all simulations were carried out on a building model with relatively high insulation values for the windows (U value: 1.50 W/m^{2}K) and opaque surfaces (U value: 0.35 W/m^{2}K); however, indoor blinds were employed to control only glare. Therefore, the optimal WWR value might increase when using an effective shading strategy, especially for the south-facing windows of a building with a spread layout.

TOC

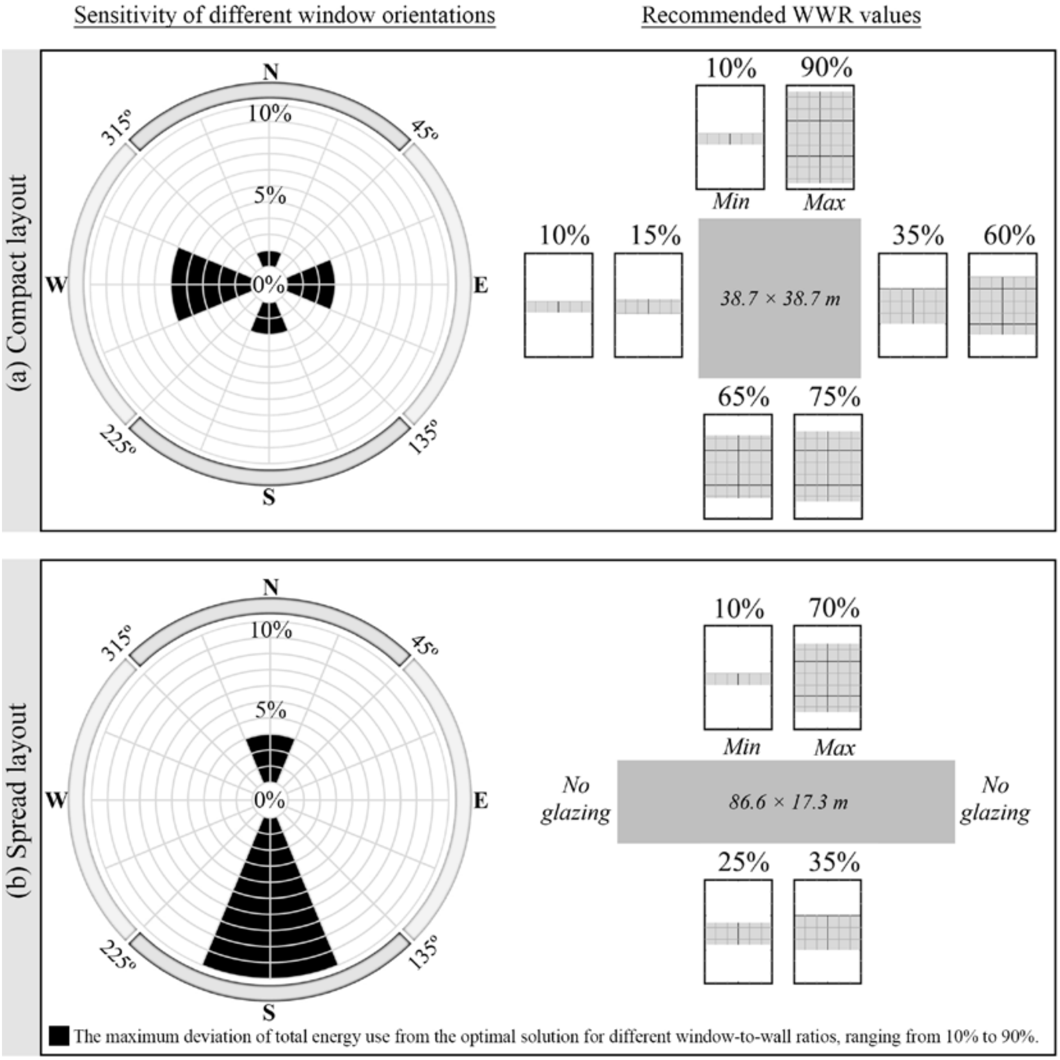


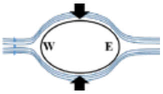
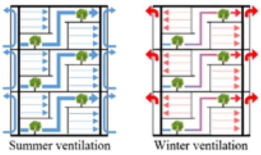
FIGURE 7.16 Sensitivity of different window orientations to a change in the WWR value (left) and the recommended values (right) for two plan scenarios: (a) compact layout, and (b) spread layout in temperate climate.

In temperate climates, a building with a double-skin façade performs better than a building with a single-skin façade in terms of energy use. The increased thermal resistance of the envelope – from two glazed skins and the air gap between them – together with the reduction of solar heat gain through a more efficient use of blinds (by placing them within the cavity instead of placing them inside the building which increases the cooling demand) can reduce the sensitivity of window orientations to a change in the WWR value; hence, higher values of WWR can be used. As shown in chapter 4, the optimal WWR of a building with a DSF with a deep cavity space (0.95 m), was found to be around 50% (for the outer leaf) when the windows are distributed evenly on the north-east and south-west facades (the longer sides of a building with a spread layout plan), while the shorter sides have no glazing. In addition, the effect of a change in WWR value (other investigated values were 30%, 80% and 100%) on total energy use was found to be insignificant (maximum deviation was around 0.3%) as long as the WWR value of the inner leaf is kept at 60%. Therefore, in temperate climates, buildings with a DSF system can take advantage of a fully-glazed outer leaf to maximize the access to daylighting and views out without compromising the energy saving targets.

§ 7.4 Proposed model of high-rise building in temperate climate

Design strategies that were discussed in the previous section (7.3) of chapter 7 are incorporated in this section to illustrate a proposed model of an energy-efficient high-rise building for temperate climates. The design strategies will include, but are not limited to, building shape, orientation, envelope elements, greenery systems and effective use of natural ventilation and daylight. The main characteristics of the proposed model of a high-rise building for temperate climates is summarized in Table 7.2.

TOC

Plan shape and orientation	
Plan layout	Open plan
Natural ventilation type	
Night-time summer ventilation	Yes
Façade type	Double-skin façade* (horizontal continuity: fully continuous along entire length of façade; vertical continuity: depends on the location between 3 and 9 storeys)
WWR	Inner leaf: 60%; outer leaf: fully-glazed
Shading	Blinds with high-reflectivity (inside the cavity)
Control of openings and shading devices	Automatically-controlled (occupants can override the BMS)
Greenery systems	
Design strategies	– Compact building shape with aerodynamic external form – Multi-storey structure double-skin façades that increase the buoyancy effect in the cavity – Stepping sky gardens connected by segmented atria – The internal configuration of plan allows public and circulation zones to be naturally ventilated separately from the occupied office spaces – Openings on two opposite directions and a narrow floor plan allow cross-ventilation for the entire office area – Wind floor (connected atria spaces) on the upper levels of every segmentation which enhances the entry of fresh air across the occupied spaces and produces additional uplift for air in the vertical shafts – Placing the service core on the east and west sides allows the central space to be open which maximizes the access to daylight and natural ventilation for inward facing offices – Curvilinear shape for external façade where it intersects with central atrium which increases air intake speed – External greenery concepts mainly on the lower levels and use vegetation more inside the building integrated with indoor sky gardens which can alleviate symptoms of discomfort among office workers resulting from sick building syndrome (SBS), regulate the average temperature and humidity of indoor air (which may enhance the thermal comfort of the occupants) and increase the productivity of office workers – On-site renewable energy generation (via adjustable solar panels and wind turbines)

** Except sky gardens that have a single-skin façade*
GR: green roof; GW: green wall; ISG: indoor sky garden

compact building form
aerodynamic building form

TABLE 7.2 The Summary of design features that are integrated with the proposed model of high-rise building in temperate climates.

The internal configuration of floor plans on each segmentation and the visual presentation of the proposed high-rise model in temperate climates are provided on Figures 7.17 and 7.18 respectively.

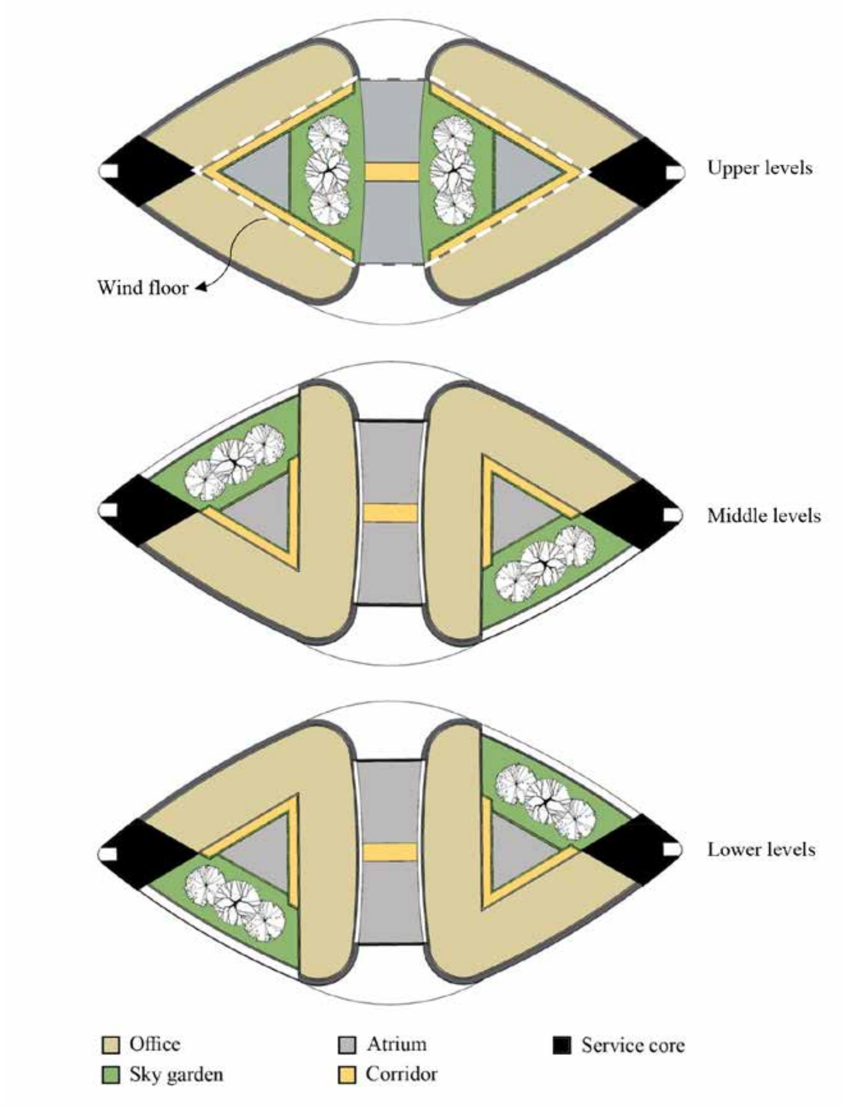
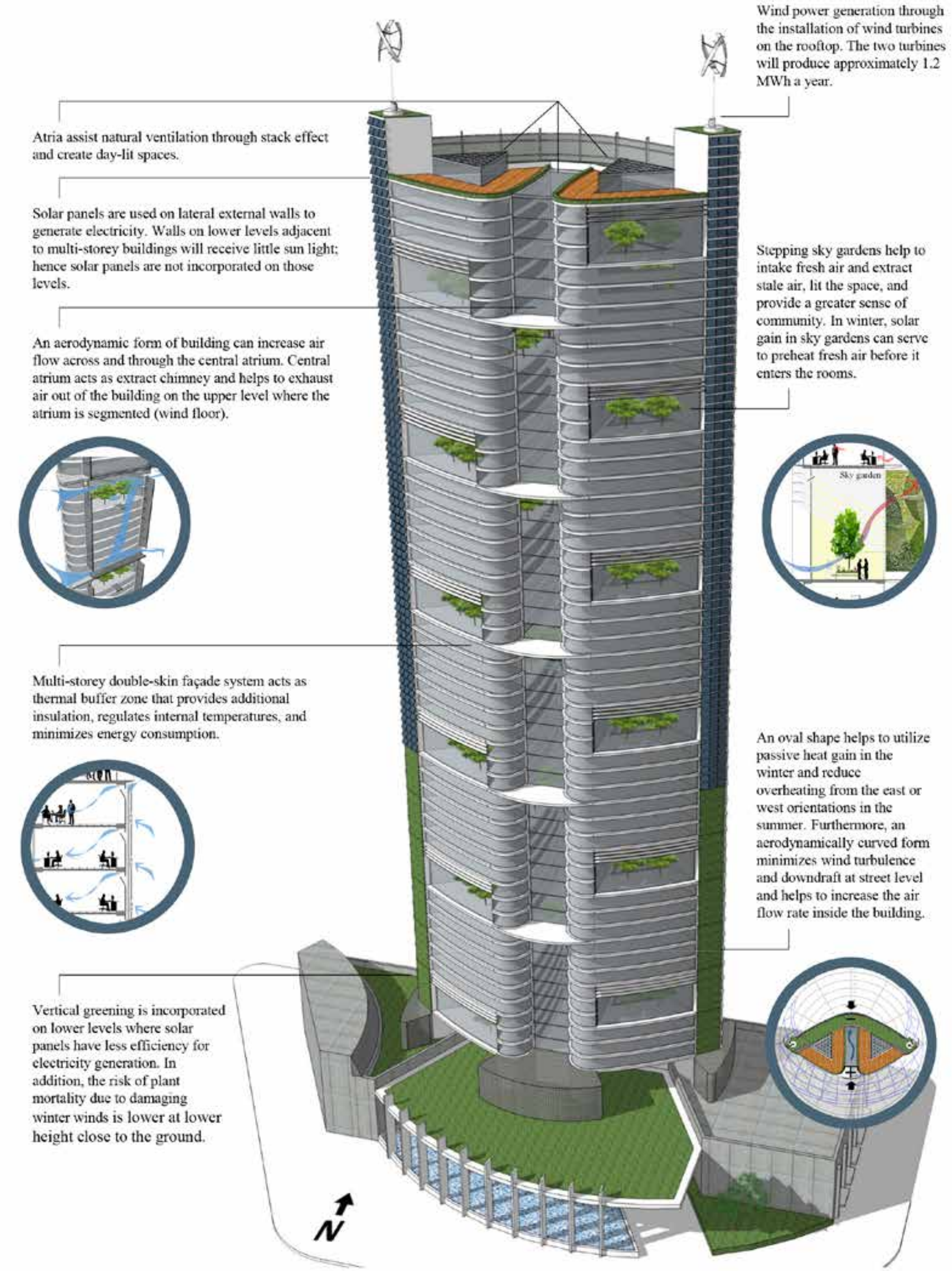


FIGURE 7.17 The configuration of floor plan on the lower, middle and upper levels at every 9-storey segmentation.



Wind power generation through the installation of wind turbines on the rooftop. The two turbines will produce approximately 1.2 MWh a year.

Atria assist natural ventilation through stack effect and create day-lit spaces.

Solar panels are used on lateral external walls to generate electricity. Walls on lower levels adjacent to multi-storey buildings will receive little sun light; hence solar panels are not incorporated on those levels.

Stepping sky gardens help to intake fresh air and extract stale air, lit the space, and provide a greater sense of community. In winter, solar gain in sky gardens can serve to preheat fresh air before it enters the rooms.

An aerodynamic form of building can increase air flow across and through the central atrium. Central atrium acts as extract chimney and helps to exhaust air out of the building on the upper level where the atrium is segmented (wind floor).

Multi-storey double-skin façade system acts as thermal buffer zone that provides additional insulation, regulates internal temperatures, and minimizes energy consumption.

An oval shape helps to utilize passive heat gain in the winter and reduce overheating from the east or west orientations in the summer. Furthermore, an aerodynamically curved form minimizes wind turbulence and downdraft at street level and helps to increase the air flow rate inside the building.

Vertical greening is incorporated on lower levels where solar panels have less efficiency for electricity generation. In addition, the risk of plant mortality due to damaging winter winds is lower at lower height close to the ground.

FIGURE 7.18 Visualization of the proposed energy-efficient high-rise building model in temperate climates.

TOC

The left-wing and right-wing offices are connected by a central atrium that provides daylight for the inward-facing offices. The centrally located atrium also plays an important role in the natural ventilation strategy of the building. Atria, sky gardens and adjacent corridors are naturally ventilated through a combination of cross ventilation and stack effect (see Figure 7.19). Fresh air enters the building through air vents at the sky gardens. Openings in the facade at the top of the central atrium exhaust the stale air out of the building. The vertical segmentation of atria divides the building into multiple compartment zones which prevents the spread of fire and development of extreme stacks or drafts. The two wings are connected by sky bridges at every 3-storeys. Internally connected spaces on the upper floors of each vertical segmentation, however, might limit the sub-division of office spaces for leasing.

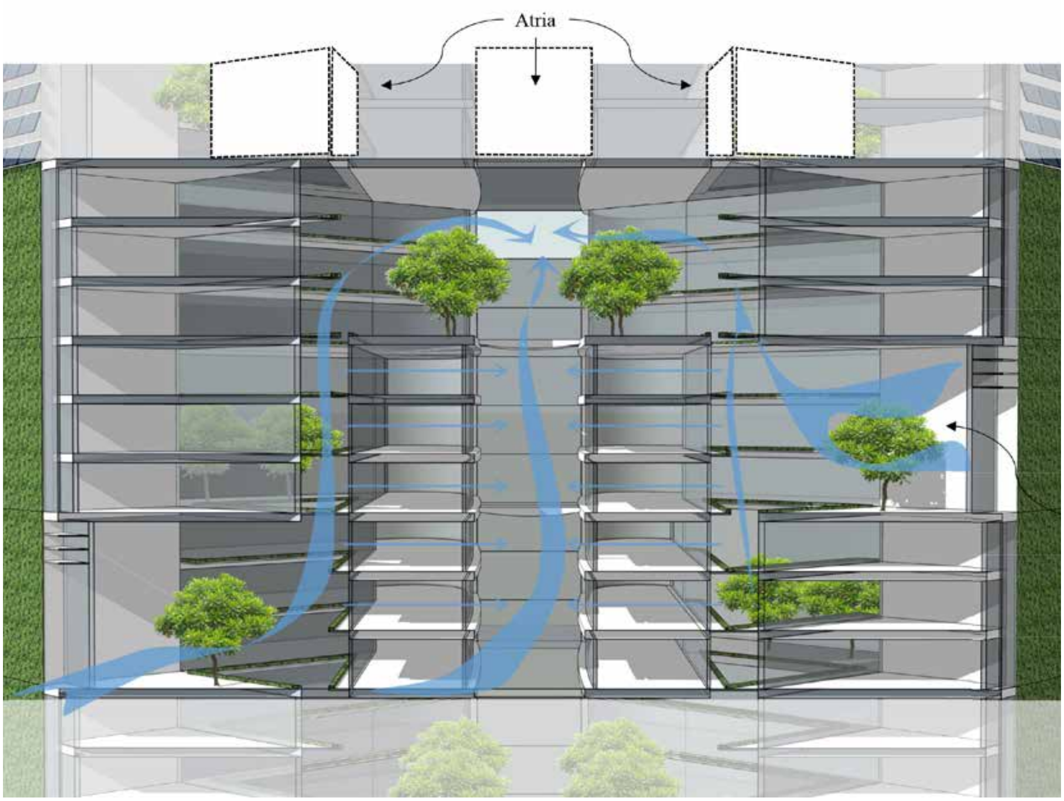
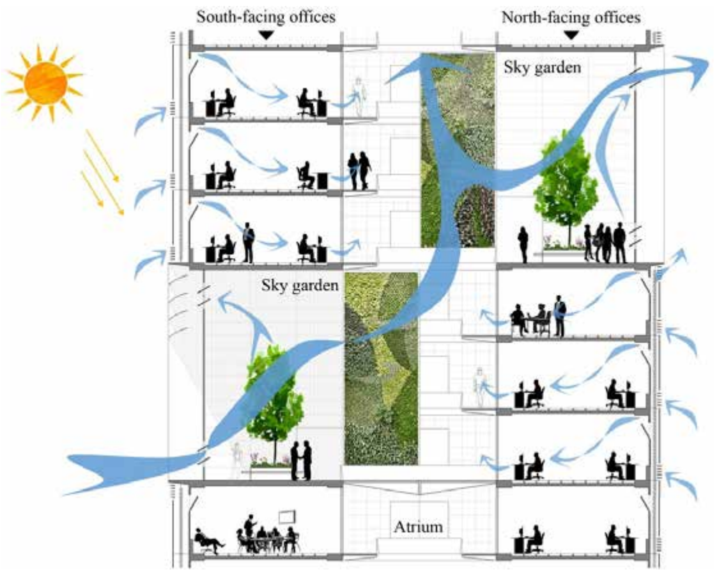


FIGURE 7.19 The intended flow pattern within the connected internal spaces on one segmentation along the building height.

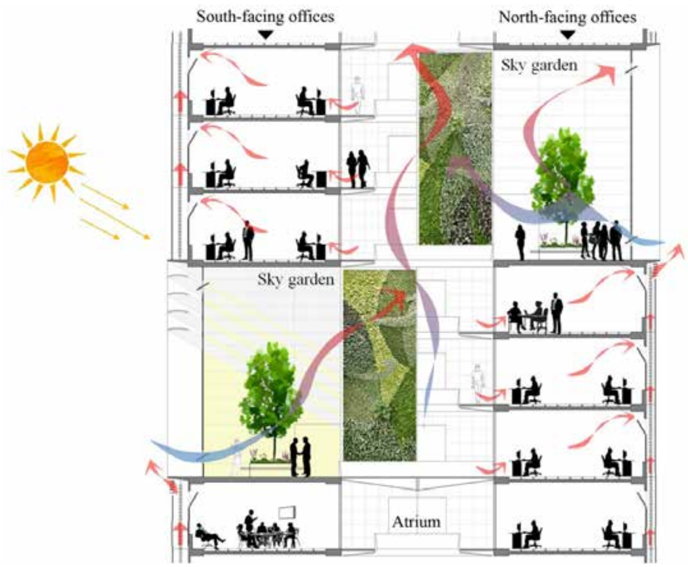
The intended air flow patterns along a north-south cross-section from the left-wing offices is presented in Figure 7.20 for two ventilation scenarios: summer and winter.

SUMMER VENTILATION



In summer, fresh air is drawn in through the DSF and sky gardens. The multi-storey DSF has air inlets at every level to reduce the risk of overheating and improving the airflow in the cavity. The fresh air then enters the offices through the operable windows on the inner leaf of the DSF. The stale air is then drawn through air grills at the bottom of internal glass partitions to the atrium where the stack effect in the atrium pulls air and exhaust the building through the wind core (central void) and partly through the sky gardens located on the leeward side.

WINTER VENTILATION



In winter, fresh air is drawn in through the sky gardens (with smaller inlet size). Solar heat gain in the sky gardens and internal gains from the occupants and equipment help to preheat cold fresh air as it passes through the atrium which is then distributed into the offices. In winter the DSF is used like a solar chimney. The air inlets of the multi-storey DSF are closed in winter to reduce the amount of heat exchange between the conditioned spaces (offices) and the cavity space. Only small air vents at the top of the external leaf of the 9-storey DSF are open. The stale air of the offices channelled through the multi-storey DSF system which warms the cavity during the winter.

FIGURE 7.20 Summer and winter natural ventilation methods.

TOC

§ 7.5 Design guidelines for tall buildings in a tropical climate

§ 7.5.1 Building form

In a tropical climate, space cooling accounts for the highest proportion of energy use in tall buildings; it considerably increases as the solar gains increase. On the one hand, a major design objective is reducing the heat transfer through the external surfaces exposed to outside high temperatures. For this purpose, a compact shape has less surface-to-volume ratio and can save more energy. On the other hand, the shape and orientation of the building should minimise the solar heat gains to lighten the cooling load. East- and west-facing walls and windows are a major factor in overheating. Therefore, extruding the floor plan along the east-west axis could help for better sun protection. The design objectives above are often contradictory.

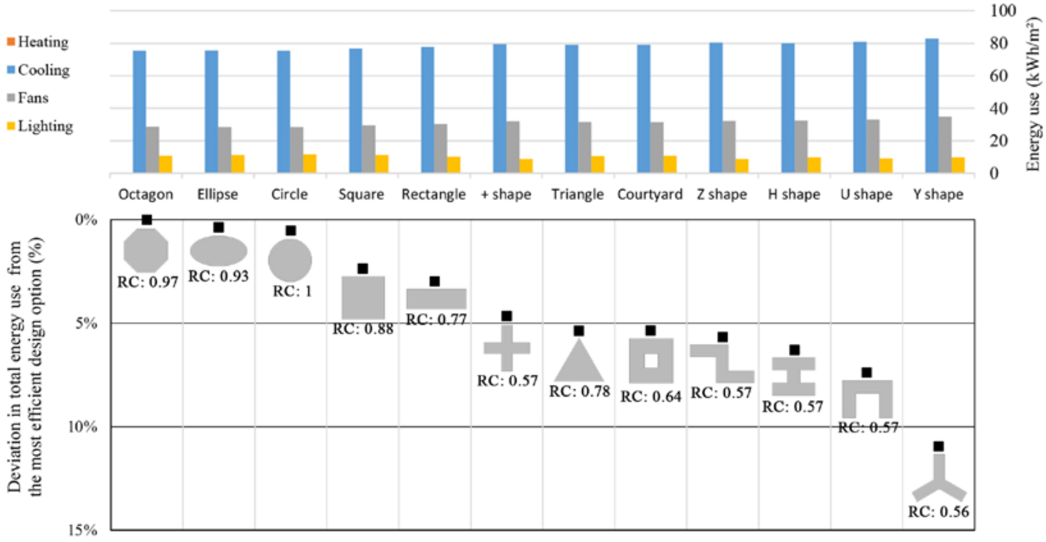


FIGURE 7.21 The maximum deviation of total energy use from the optimal solution for different plan shapes and their breakdown of total energy use in tropical climates.

TOC

As shown in chapter 3, three shapes including the octagon, the ellipse and the circle required a lower amount of cooling energy and performed better than the others (see Figure 7.21). When using compact shapes, east- and west-facing facades need effective solar control strategies to prevent excessive heat gain into the internal spaces. In this regard, the most effective design strategies for reducing the solar gains on the hot sides are a lower percentage of window-to-wall area, high-performance shading devices (adjustable external shades or a higher coverage of fixed louvers), peripheral service cores, recessed balconies, and greenery systems. Balconies should be placed such that they cut off direct solar radiation during the hot hours of the day and enhance natural ventilation. Otherwise the effect of heat transfer through the increased surface will offset the shading effect by recessed terraces. The application of greenery on external walls (or balconies) facing east and west can reduce the surface temperatures through shading and evapotranspiration but should not block the air flow through the windows. While a peripheral location of a service core contributes effectively to reducing the cooling loads and provides the possibility of using natural ventilation and daylight in these service areas, it is important to consider the influence of increased electric lighting demand for office spaces. Office areas that are located in the deeper parts of the floor plan receive less daylight and need therefore more energy to supply artificial light. Application of a central atrium or sky gardens are essential to bring natural ventilation and daylight deep into the building when the percentage of peripheral offices along the external façade becomes lower.

§ 7.5.2 Building orientation

The impact of a change in orientation on the total energy use is lower in tropical climates (7.9%) than in temperate climates (15.1%). In case of a compact plan layout (1:1), the maximum deviation – in total energy use – between the most and least efficient orientations is 0.7%, while these differences can rise to a peak at around 7.9% for very narrow plan layouts (10:1) (see Figure 7.22). A zero-degree orientation optimally keeps out solar radiation in the early morning or afternoon in tropical climates and results in the lowest energy consumption. Rotating the building 90° increases the energy use of the building to a large extent. A 45° rotation of the building can reduce the west exposure to the hot afternoon sun (in case of elongated shapes), hence results in a better performance than a 135° and 90° rotation.

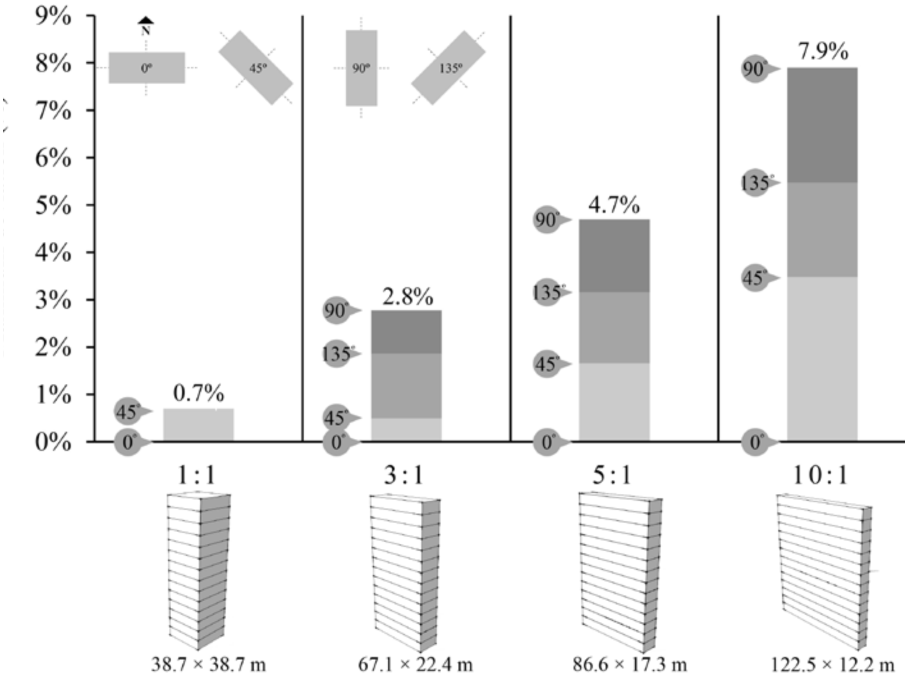


FIGURE 7.22 The percentile difference in the total energy use between the most and least efficient orientation for different plan layouts in tropical climate.

§ 7.5.3 Natural ventilation

A natural ventilation strategy that employs wind and buoyancy driving forces together can provide greater chances of having higher indoor velocities under different wind conditions so that comfort conditions can improve and less cooling will be needed. My findings showed an increase in the average and maximum indoor air velocity by adding a vertical shaft into the central core of a deep floor plan building on a calm day with no particular wind. The average percentage (at different floors under different weather scenarios) of comfort area with the application of a full-height atrium was by around 10% higher than a wind-induced ventilation strategy. The maximum difference in the area of comfort exists in scenario 2 when cross ventilation can hardly occur, as shown in Figure 7.23.

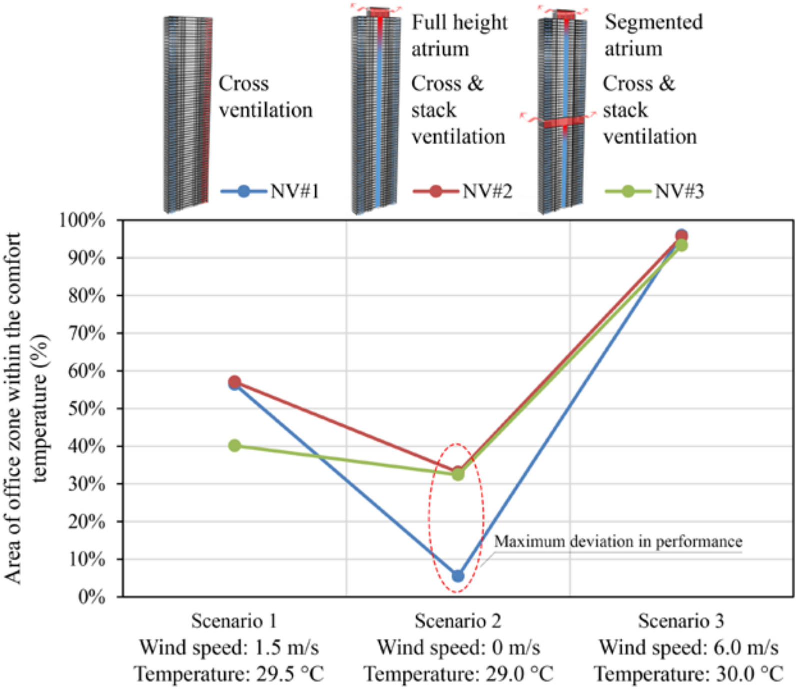


FIGURE 7.23 A comparison of indoor comfort conditions among three natural ventilation strategies under three different weather scenarios.

When the stack effect is the dominating driving force for natural ventilation (in the absence of wind), the air that enters the upper floor comes from the shaft and is therefore stale air and cannot be regarded as fresh air. In such conditions, the integration of sky gardens into the atrium – for air supply and exhaust – and segmentation of the atrium along the building height are passive strategies that can effectively reduce stale air accumulation on the upper floors. Furthermore, my findings showed that the top floor of a building that employs a full-height atrium needs supplementary mechanical ventilation during a higher percentage of occupancy time (about 3%) than a segmented atrium. In regards to fresh air requirements, an assistant mechanical ventilation system besides natural ventilation might be essential for at least 10% of the occupancy time on certain floors. Those floors that are in higher demand of mechanical ventilation are the lower floors of a building with a wind-induced ventilation strategy, and the middle and upper floors of a building with a buoyancy-induced ventilation strategy.

The range of comfort area is increased to a peak value at around 95% in scenario 3. This indicates the importance of elevated velocities for improving thermal comfort conditions in hot and humid climates, although the high range of comfort here is

TOC

primarily caused by a higher wind speed (6 m/s) in scenario 3. Generally, low wind speeds, small stack effects and outdoor air temperatures that are close to the upper comfort temperature limits make the implementation of natural ventilation strategies more challenging in tropical climates. Therefore, the building form and orientation, envelope design and interior layout should be able to facilitate the air flow across the interior spaces and to induce greater velocities. Curved or funnel-shaped structures can be used to lead the wind in desired directions. Another effective strategy to capture wind from a wide range of directions is through the outward extension of walls (wind wing walls) when site limitations do not allow to orient the building along the prevailing wind axes.

§ 7.5.4 Façade type

According to the simulation results of chapter 4, the amount of cooling and lighting energy use that is needed for a single-skin façade system is lower than a DSF system in tropical climates. A large portion of useful daylight cannot be transferred into the building through a DSF system. This will result in an increase of electric lighting demand. Moreover, the cavity of a poorly ventilated DSF building can get easily warm so there is a higher risk of overheating. Apart from that, the air flows at higher speeds when there is less resistance in the flow path, so greater velocities can be expected through a single-skin façade building. For these reasons, a single-skin façade system is a better option for tall buildings in tropical climates.

§ 7.5.5 Shading

In tropical climates, external shading strategies such as overhangs or louvers provide the best energy performance, while the lowest efficiency is related to the application of indoor blinds, particularly if low-reflectance slats and low-emissivity (low-e) glazing are used. In cities close to the equator, north and south façades need fixed horizontal shades (such as overhangs) to cover high sun angles, whereas east or west facades require adjustable shades or higher coverage of fixed louvers to block a wide range of sun angles.

§ 7.5.6 Glazing type

Solar heat gain through windows is a major factor determining the cooling energy requirements of a building in tropical climates. Therefore, the selection of an appropriate type of glazing that can control both visual and thermal comfort is critical. In tropical climates, the solar heat gain coefficient (SHGC) of the glazing should be kept as low as possible, while a high light transmission coefficient can help to lower electric lighting demand. Spectrally-selective glazing (SHGC: 0.42 and light transmission coefficient: 0.68) is the most favourable option for office buildings that need high light levels and have a long cooling season. According to our findings in chapter 5, the impact of the U value of the glazing on the building's energy-efficiency is lower than the impact of the SHGC and the light transmission coefficient in tropical climates.

§ 7.5.7 Window-to-wall ratio (WWR)

When it concerns the energy efficiency of buildings in tropical climates, a high WWR can increase the risk of overheating and raise the cooling demand. In the tropics east and west are the most sensitive orientations that potentially increase the total energy use (relative value) to a large extent for a wrong selection of WWR. The east- and west-facing walls, therefore, should avoid high WWR values particularly when high-performance shading devices are not incorporated. Our investigations showed that it is important to keep the WWR at the minimum value (10-20%) for the east- and west-facing windows in order to keep the deviation of total energy use to lower than 1% for a deep plan building with indoor blinds (only for glare control) (see Figure 7.24). However, the north- and south-facing windows can have a wider range of WWR values for the same energy saving target. In case of a spread plan layout, a wrong selection of WWR for the north- and south-facing facades can cause a higher increase in the total energy use (+8.6% and +3.2%, respectively).

TOC

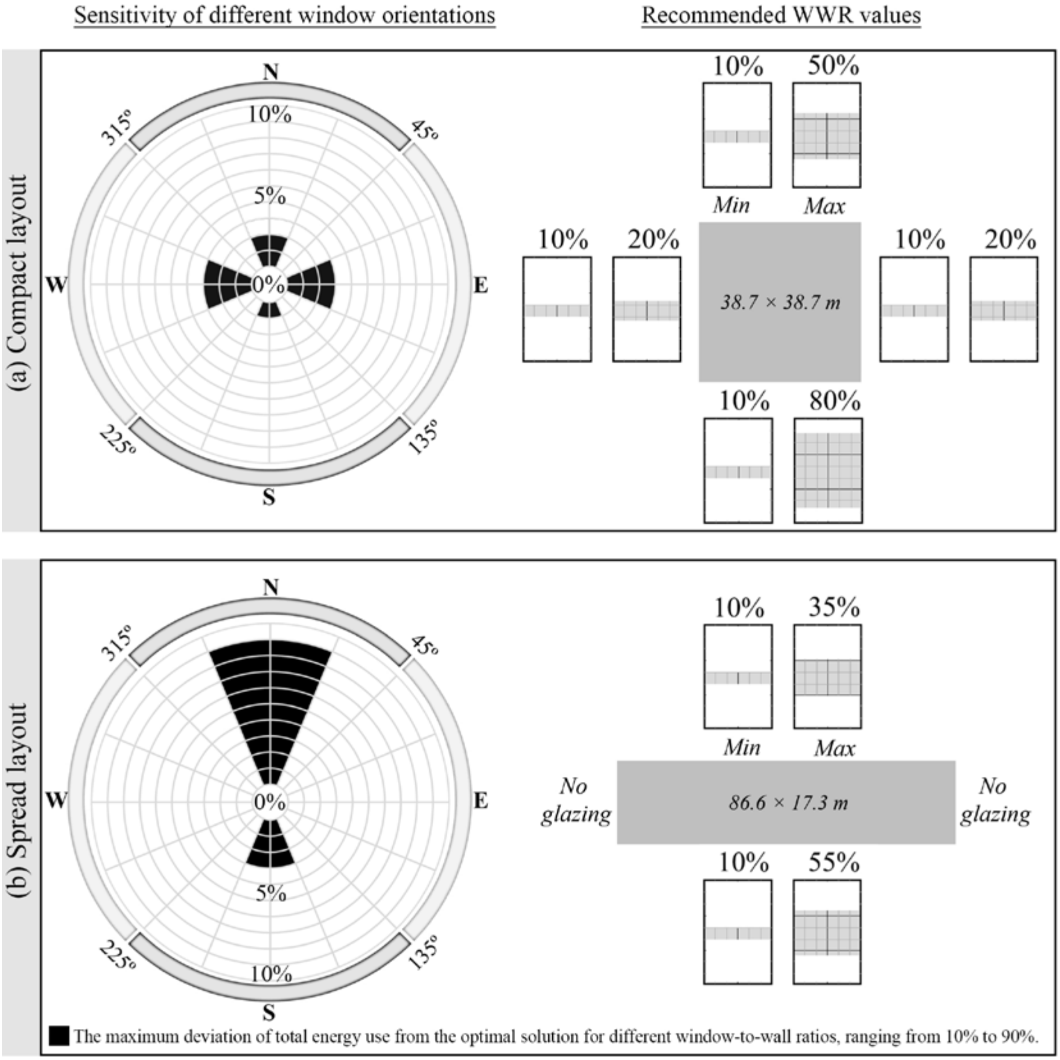


FIGURE 7.24 Sensitivity of different window orientations to a change in the WWR value (left) and the recommended values (right) for two plan scenarios: (a) compact layout, and (b) spread layout in tropical climate.

For each individual glazing type and shading system (or their combination), the optimal WWR might have a different range. Specially, the effect of shading is more dominant in selecting the optimal range of WWR. In absence of a shading system, the glazing characteristics (such as SHGC and light transmission) have a dominant impact on the building’s energy performance. When the windows are distributed evenly among all directions of a compact plan layout, the optimal WWR for improving daylight access and reducing heat gain is around 40% for spectrally-selective glazing (see Table

7.3). With the use of a high-performance shading strategy (using a combination of overhang and louvers with higher coverage on the east and west sides), the optimal WWR value can be raised to 80% (or more if possible). It is important to note that a high WWR should only be recommended for buildings with effective solar heat transmission control strategies. Low sun angles in the morning and evening are a source of glare when daylighting is provided through east- and west-facing windows. As a result, high WWR values are not recommended even if the building is featured by effective solar heat control systems.

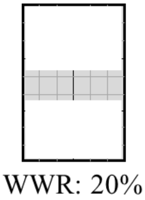
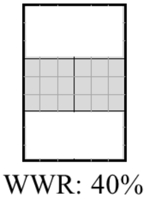
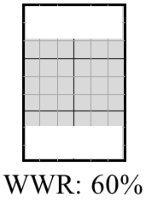
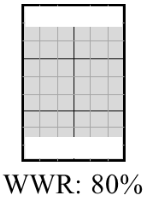
	PERCENTAGE OF DEVIATION IN TOTAL ENERGY USE FROM THE OPTIMAL WWR (%)			
Window-to-wall ratio (WWR)				
No shading	10.0%	Optimal value	0.5%	2.1%
High-performance shading	17.2%	13.3%	5.6%	Optimal value

TABLE 7.3 The optimal WWR for spectrally-selective glazing when the windows are distributed evenly among all directions for two shading scenarios: no shading, and with the use of a high-performance shading.

§ 7.5.8 Service core placement

The use of buffer components such as service cores could have important effects on the building's energy performance in tropical climates. The location of the service core determines the internal configuration of the plan and the distribution of windows, as well as, the potential use of daylight and natural ventilation strategies. For deep plan buildings that are fully-mechanically ventilated, a central core is more beneficial energy-wise when the building's façade is featured with a high-performance design. While the cooling energy use is almost equal for the different core positions, the differences in total energy use are mostly resulting from electricity usage for artificial lighting. Service cores that are located along the external façade can be lit naturally, however, in that case more artificial light should be supplied to the office spaces (which are in higher demand for lighting). For naturally ventilated buildings, placing the service core along the façade provides this possibility to be naturally ventilated, while the central part the building plan can be allocated to an atrium for bringing daylight deeper into the building and for distributing the fresh air in a relatively more uniform manner throughout the entire plan.

§ 7.5.9 Zone-based ventilation strategy

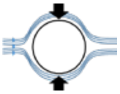
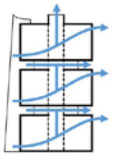
A zone-based ventilation strategy could result in a high amount of energy saving for cooling and ventilation of high-rise buildings in tropical climates. The internal plan configuration should allow public or circulation zones within a floor plan to be naturally ventilated separately from the occupied office spaces. Office workers expect a high degree of comfort at their work stations but tolerate a little bit of discomfort in lift lobbies and communal spaces. In this way, the public/circulation zones in the building can benefit from natural ventilation during a longer period of occupation annually. Office zones can utilize their own dedicated air-handling units so they could switch the system to mechanical when the external conditions do not allow for natural ventilation.

§ 7.5.10 Roof shading and roof-mounted PV panels

In high-rise buildings, the roof takes up a lower percentage of the total external surface area therefore the effect of energy-saving strategies targeting the roof can be very small and limited mostly to the top floor. However, in order to protect the top floor from overheating, it is important to control solar heat transmission through the roof structure. According to our findings in chapter 5, adding a shading structure made of high-reflective aluminium coating at 3.5 m distance above the roof could reduce the heat transfer more than the other roof strategies (green roof or reflective roof) and may lead to 0.2% energy saving for cooling and total energy use. This is regardless of the electricity that can be produced by PV cells on the shading roof.

§ 7.6 Proposed model of high-rise building in tropical climate

Design strategies that were discussed in the previous section (7.5) of chapter 7 are incorporated in this section to illustrate a proposed model of an energy-efficient high-rise building in tropical climates. The main characteristics of the proposed model of high-rise building in tropical climates is summarized in Table 7.4.

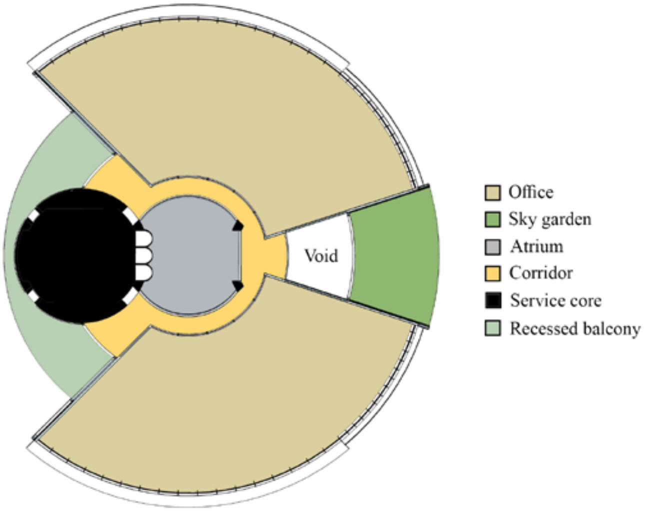
Plan shape	
Plan layout/depth	Open plan (15 m from central void)
Natural ventilation type	
Night-time summer ventil.	No*
Façade type	Single-skin façade (using double-glazed low-e spectrally selective clear glass for windows)
WWR	North and south: WWR=80%; east and west: WWR=VAR (the WWR value is higher where recessed balconies and sky gardens provide permanent deep shading for the external façade, but lower values have been used where the external facade is exposed to solar gains; e.g. on the external surface of service core the WWR value is 15%)
Shading	Overhangs (on the north and south façades) and louvers (on the east façade) Recessed balconies are incorporated on each floor on the west façade and every six-storeys on the east façade
Control of openings and shading devices	Automatically-controlled (occupants can override the BMS)
Greenery systems	
Design strategies	– Compact building shape – Curved and funnel-shaped building form which help to lead the wind from a wide range of directions into the building and induce higher velocities within the ventilated spaces – Two-storey wind floors on top of the central atrium at every 6-storeys along the building height – The internal configuration of plan allows public and circulation zones to be naturally ventilated separately from the occupied office spaces – Openings on two opposite directions and a relatively narrow floor plan allow cross-ventilation for the entire office area – The two office zones on each floor plan have a funnel-shaped layout which help improve cross ventilation between the two opposite openings – Placing the service core on the west side allows the central space to be open which maximizes the access to daylight and natural ventilation and act like a thermal buffer space prevent hot afternoon sun to enter the building – Recessed balconies on the west façade and multi-story sky gardens on the east façade provide the possibility of using larger windows to assist natural ventilation while preventing the low-sun angles to penetrate into the internal spaces – External greenery concepts are incorporated on different floors along the entire building and in the form of green walls, green roofs, green balconies and sky gardens which contribute in energy saving and CO2 intake – On-site renewable energy generation by adjustable solar panels on the rooftop

** Not effective in tropical climates due to insignificant day/night temperature differences*
GR: green roof; GW: green wall; SG: sky garden; GB: green balcony

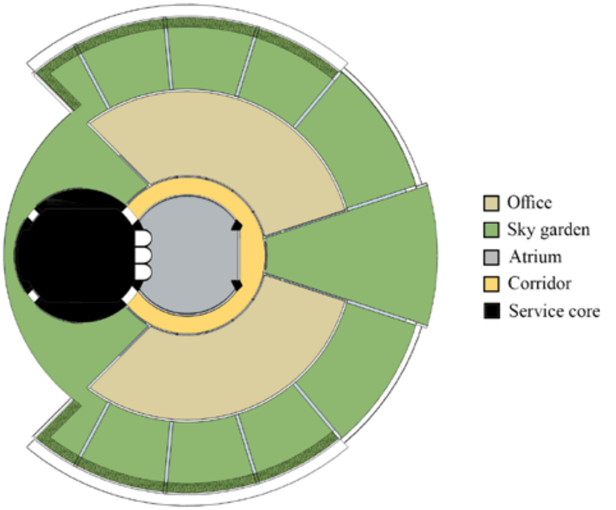
compact building form
aerodynamic building form

TABLE 7.4 The Summary of design features that are integrated with the proposed model of high-rise building in tropical climates.

The internal configuration of floor plans on each segmentation and the visual presentation of the proposed high-rise model in tropical climates are provided on Figures 7.25, 7.26 and 7.27.

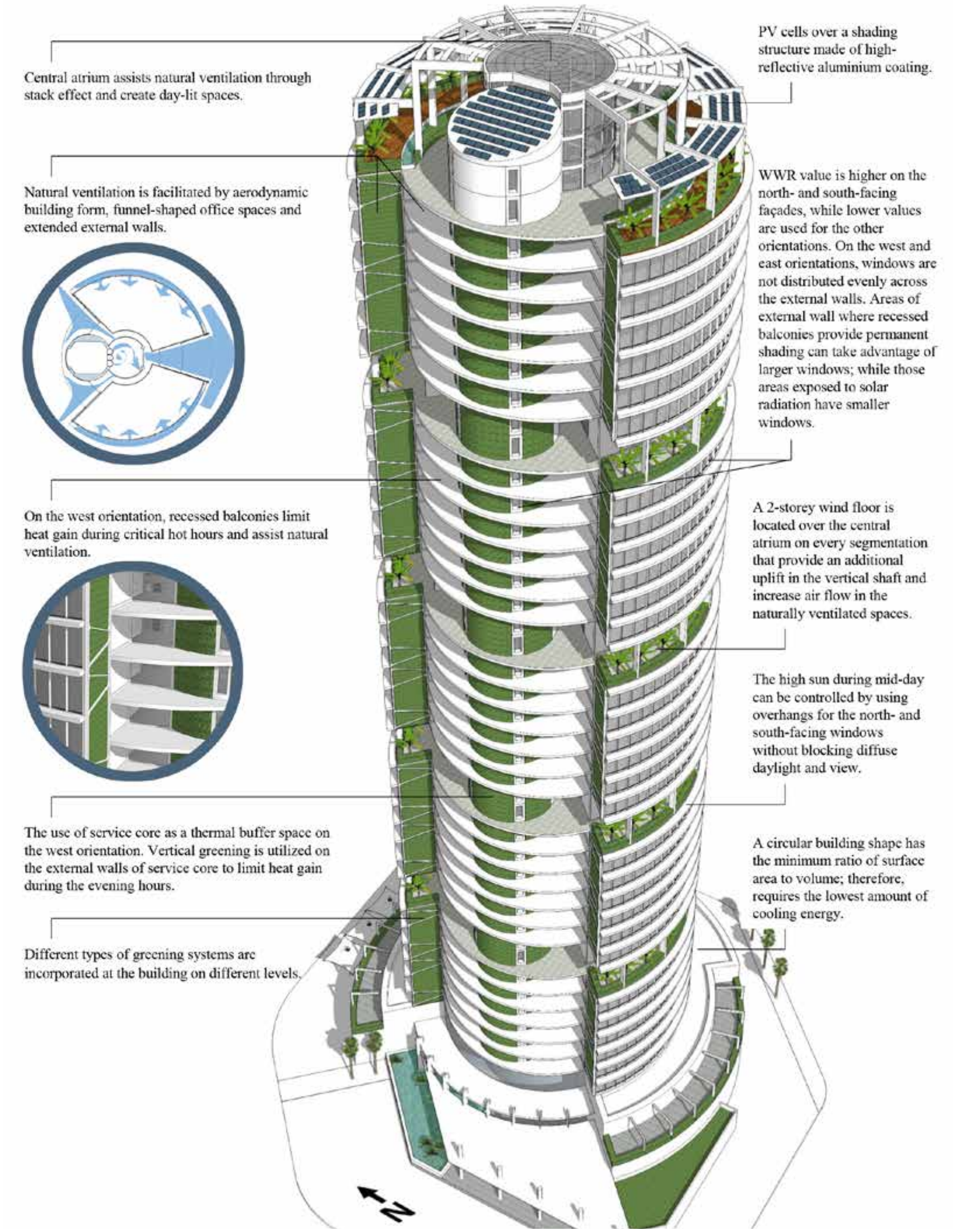


Typical floor plan



Wind floor plan

FIGURE 7.25 The configuration of internal spaces on a typical floor plan and a wind floor plan at every 8-storey segmentation.



Central atrium assists natural ventilation through stack effect and create day-lit spaces.

Natural ventilation is facilitated by aerodynamic building form, funnel-shaped office spaces and extended external walls.

On the west orientation, recessed balconies limit heat gain during critical hot hours and assist natural ventilation.

The use of service core as a thermal buffer space on the west orientation. Vertical greening is utilized on the external walls of service core to limit heat gain during the evening hours.

Different types of greening systems are incorporated at the building on different levels.

PV cells over a shading structure made of high-reflective aluminium coating.

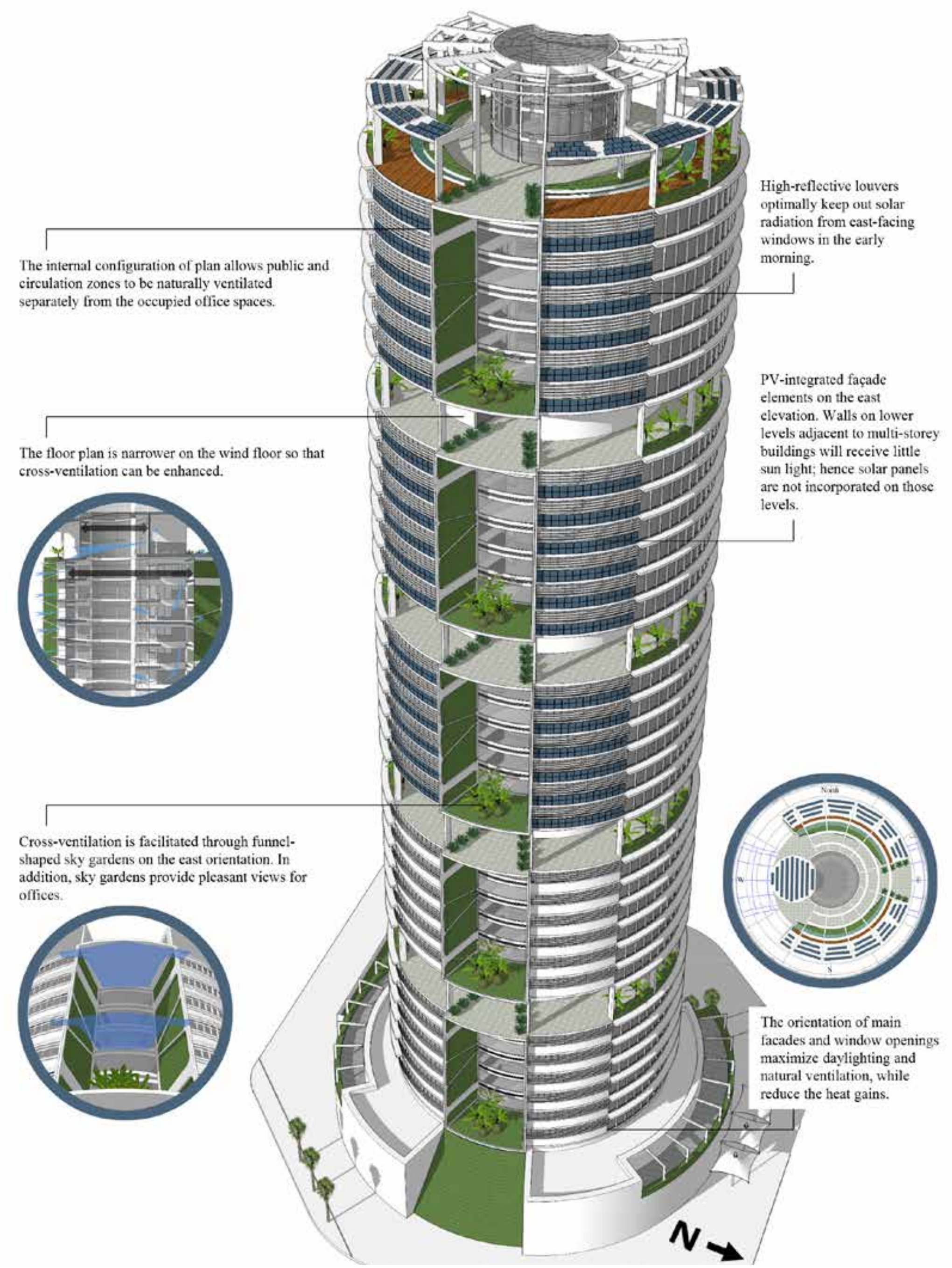
WWR value is higher on the north- and south-facing façades, while lower values are used for the other orientations. On the west and east orientations, windows are not distributed evenly across the external walls. Areas of external wall where recessed balconies provide permanent shading can take advantage of larger windows; while those areas exposed to solar radiation have smaller windows.

A 2-storey wind floor is located over the central atrium on every segmentation that provide an additional uplift in the vertical shaft and increase air flow in the naturally ventilated spaces.

The high sun during mid-day can be controlled by using overhangs for the north- and south-facing windows without blocking diffuse daylight and view.

A circular building shape has the minimum ratio of surface area to volume; therefore, requires the lowest amount of cooling energy.

FIGURE 7.26 West- and south-facing facades of the proposed energy-efficient high-rise building model in tropical climates.



The internal configuration of plan allows public and circulation zones to be naturally ventilated separately from the occupied office spaces.

High-reflective louvers optimally keep out solar radiation from east-facing windows in the early morning.

The floor plan is narrower on the wind floor so that cross-ventilation can be enhanced.

PV-integrated façade elements on the east elevation. Walls on lower levels adjacent to multi-storey buildings will receive little sun light; hence solar panels are not incorporated on those levels.

Cross-ventilation is facilitated through funnel-shaped sky gardens on the east orientation. In addition, sky gardens provide pleasant views for offices.

The orientation of main facades and window openings maximize daylighting and natural ventilation, while reduce the heat gains.

FIGURE 7.27 East- and north-facing facades of the proposed energy-efficient high-rise building model in tropical climates.

Fresh air enters the building through recessed balconies on the west orientation and through the operable windows along the external façade of the office spaces (see Figure 7.28). Openings on two opposite directions and a relatively narrow floor plan allow cross-ventilation for the entire office area. The stale air is then drawn through air grills at the bottom of internal glass partitions to the atrium where the stack effect in the atrium pulls air upward. A 6-storey sky garden on the east direction funnels part of the stale air out of the building through the exhaust openings on every three floors. A wind floor is located on the top of the central atrium for each segmentation that provides an additional uplift in the vertical shaft (central atrium); hence plays an important role in increasing the air velocity in the naturally ventilated spaces and reducing the risk of a reverse flow through the atrium. In the proposed design, different strategies are incorporated to prolong the duration of natural ventilation. Certain zones in the building such as circulation areas and communal spaces can be naturally ventilated throughout the entire year. In this building, the natural ventilation strategy employs wind and buoyancy driving forces together. So, it can provide greater chances of having higher indoor velocities under different wind conditions. Finally, natural ventilation is facilitated by using an aerodynamic building form, funnel-shaped spaces (for the offices and the sky gardens) and extended external walls (wind wing walls).

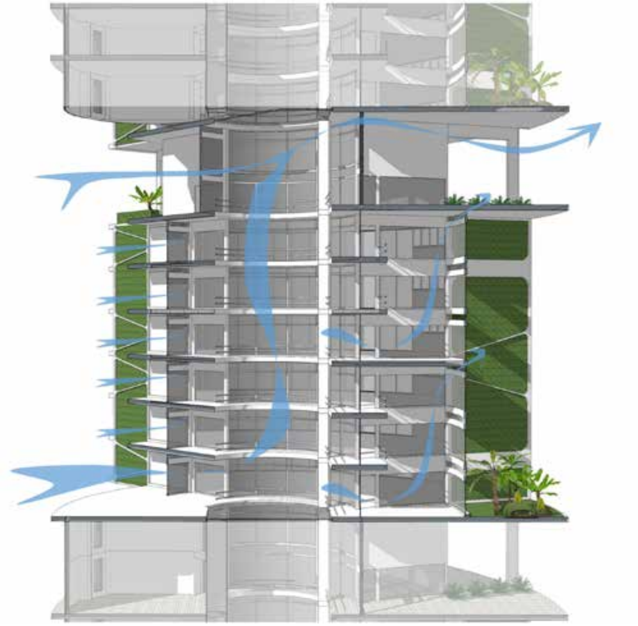


FIGURE 7.28 The intended flow pattern within the connected internal spaces on one segmentation along the building height.

§ 7.7 Conclusion

In this chapter, the essential energy saving strategies and sustainability features for the design of tall office buildings have been discussed for temperate and tropical climates. In addition, the outcomes were used to design a conceptual model of an energy-efficient high-rise office building in the temperate and tropical climates. It is expected that the presented architectural strategies and the use of renewable sources for the proposed building models can significantly minimise the building's dependency on fossil fuels and can lead to higher occupant satisfaction with indoor environmental quality compared to conventional designs.

In conventional commercial buildings, decisions regarding the shape of plan and the internal configuration of spaces are commonly influenced by dated short-term visions (such as maximizing the ratio of net leasable area to gross floor area). This is a major obstacle to the development of high-performance design in commercial tall buildings. To limit the number of ineffective designs, there is a need to apply a broader range of assessments during the decision making that include additional factors such as well-being and productivity of occupants, and buildings' share of carbon dioxide emissions coming from energy consumption.

Tall buildings, by their nature, offer designers great opportunities for reducing their dependency on fossil fuels. They generally stand well clear of their adjacent buildings. Therefore, they are open to more consistent wind flow and solar exposure than low-rises. Orienting the building to ensure maximum exposure to sun and wind energy streams is the most important step for energy efficiency. Furthermore, there should be a variation in envelope design and the selection of measures on different orientations according to sun path, wind direction, and adjacent buildings. In this regard, one extruded form inspired by a single plan that is fully-glazed on all directions does not make sense.

In sustainable buildings, designers should allocate a relatively larger portion of usable floor space to semi-open spaces such as atria and sky gardens. Such spaces can create a sense of community up in the sky. The presence of natural light, appealing views and natural ventilation through such spaces can improve the comfort of workers, as well as their perception of the quality of their environment; hence increase their productivity. These spaces can also reduce the energy consumption and reliance on mechanical systems. Finally, greenery systems should be integrated to the design of tall buildings, both internally and externally. The presence of vegetation can improve environmental quality on both the building scale and the city scale. These recommendations form an acceptable starting point for improvements to tall building design and could be of assistance to make energy-wise decisions during the design process.

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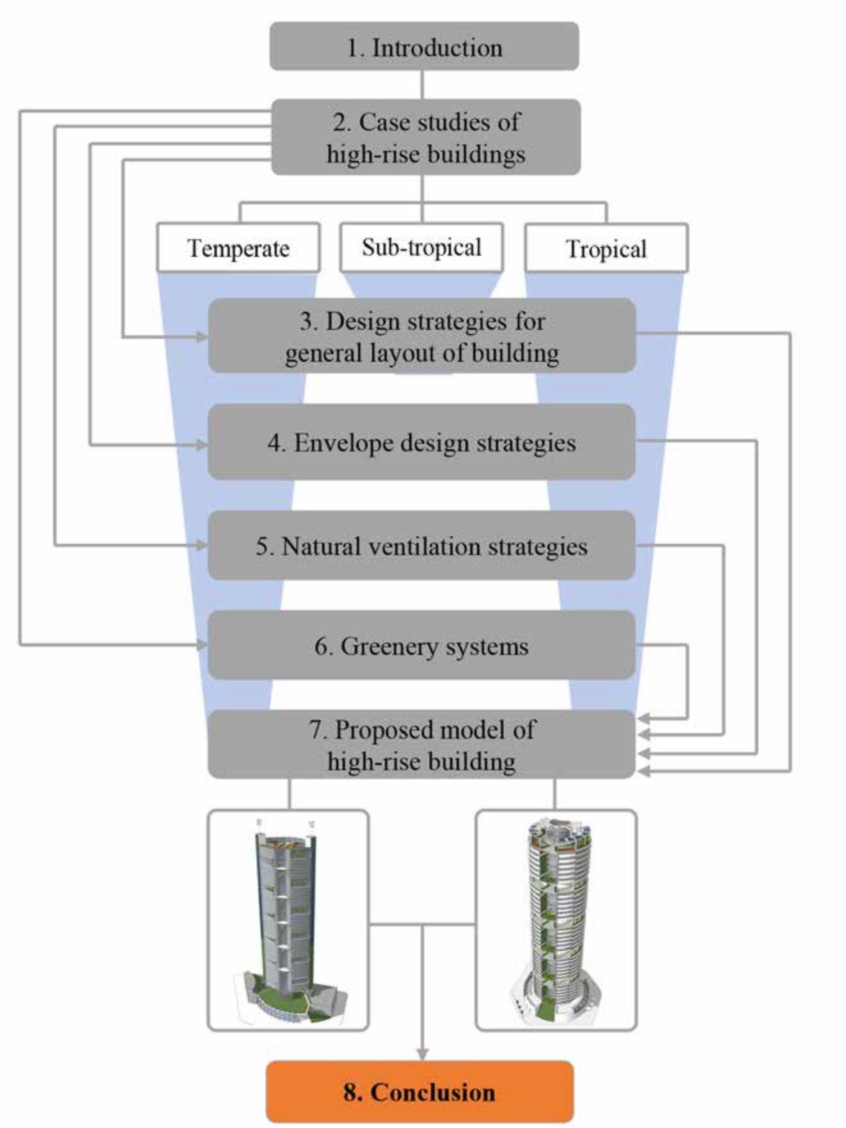
1. Introduction
2. Case studies of high-rise buildings
Temperate
Sub-tropical
Tropical
3. Design strategies for general layout of building
4. Envelope design strategies
5. Natural ventilation strategies
6. Greenery systems
7. Proposed model of high-rise building
8. Conclusion

8 Conclusion

§ 8.1 Introduction

With the aim to limit the number of ineffective designs, this research has investigated the impact of architectural design strategies on improving the energy performance of and thermal comfort in high-rise office buildings in temperate, sub-tropical and tropical climates. The starting-point of the research was a comparative study between nine sustainable and three conventional high-rise office buildings concerning their energy performance and the use of architectural design strategies. Lessons from these buildings were defined for the three climates. As a next step, simulation studies were carried out to quantify the impact of geometric factors, envelope elements and natural ventilation strategies on energy consumption and thermal comfort of high-rise buildings. Through an interdisciplinary literature review, the contribution of greenery systems for improving the energy-efficiency, thermal comfort and indoor air quality of high-rise office buildings was discussed as well. Chapter 7 consolidated the findings from previous chapters to point out general and climate-specific design strategies that are required for energy-efficiency of tall office buildings. The outcomes were used to illustrate a proposal for an energy-efficient high-rise office building in the temperate and tropical climates.

This chapter finally presents the conclusions of this dissertation. First, the research questions are revisited, answered and discussed. Afterwards, a critical overview of limitations and challenges is provided. Recommendations for the future applicability of the results and for the further development of research is discussed in section 8.4. The last part of this chapter consists of a general discussion of findings.

§ 8.2 Answers to the research questions

This section gives detailed answers to the sub-research questions. Each sub-question addresses a corresponding chapter. The answers to the main research questions are provided in section 8.5 as the general discussion of findings.

Question 1 (chapter 1)

a) What is the best method to quantify the impact of architectural design strategies on energy consumption and thermal comfort of high-rise buildings?

b) How can architects benefit from the results of this study for improving the performance of high-rise office buildings?

The design recommendations defined in this study were based on a combination of theoretical guidelines, data from secondary (literature) sources, high-performance design references, international standards and simulation-based performance assessments. While field studies are of great importance for post-occupancy evaluations, they are not feasible for performance assessment in the design phase of high-rise buildings, due to constraints related to time, cost and scale. Simulation studies, if well-validated, allow multi-directional assessment of design parameters in a controlled environment. In order to quantify the impact of architectural design strategies on energy consumption and thermal comfort, both energy and CFD simulations were employed. DesignBuilder's fully-integrated approach provides this possibility to develop one core model and use it to run a variety of assessments using different engines (EnergyPlus and CFD).

To increase the generalisability of findings for diverse projects/contexts and to give the designers more freedom on their decisions, the main part of the research is allocated to a discussion on how an architectural design strategy can affect heating, cooling, ventilation and electric lighting loads and how design strategies can influence each other. The best design solutions – among other alternatives – were selected by taking the final energy use as the efficiency indicator. The effectiveness of other design alternatives was determined by calculating the deviation of their total energy use from the most efficient design option. This method gives a higher freedom to select design strategies that suit the energy saving targets and the design brief of a project best. The research outcomes, therefore, can assist designers, clients and users to make efficient choices.

Question 2 (chapter 2)

What are the design differences between typical and sustainable high-rise office buildings in temperate, sub-tropical and tropical climates?

To answer this question, a comparative study on twelve case buildings in three climate groups (temperate, sub-tropical & tropical) was performed. For each climate group, three sustainable high-rises were selected and one typical, non-sustainable high-rise design as a reference. The effectiveness of design approaches for reducing the energy for cooling, heating, ventilation and electric lighting was analysed. Multiple sources of evidence were used to increase the validity of findings by means of: (1) comparing the building-related energy performance data of each group of buildings in one climate, (2) comparing the total energy use of twelve case studies with related energy benchmarks in each climate/context, and (3) comparing the mean monthly outdoor air temperature with comfort temperatures in each climate or context based on adaptive thermal comfort (ATC) models versus predicted mean vote (PMV) models, respectively for buildings with natural ventilation and air conditioning systems. Building-related energy performance data of each group of buildings were collected through contact with the energy consultants involved in the respective building, and by using data from literature. In addition, necessary conversions were done to make the energy figures comparable. Design principles of sustainable and conventional high-rise office buildings were defined.

The main design principles were substantially similar among conventional high-rise buildings, irrespective of the climate type, aside from small differences affected by the advancements in building technology or construction regulations related to the time or place of construction. The environmental factors were not taken into consideration for the building orientation (e.g. the EWI building). For the selection of building form, right-angled shapes were more common. Generally, the ratio of lettable to gross floor area was higher, except for the Empire State building, for which both the construction period and excessive height required more space to be allocated to service areas. The building layout was typically composed of one extruded form inspired by a single plan (all the three conventional case studies) and the same design strategies were utilised irrespective of the façade orientation. The buildings entirely relied on air conditioning, and due to a deep plan, there was a higher demand for electric lighting. The service core was typically located in the centre of the floor plan. The windows were distributed evenly among all directions and there was no (effective) shading system to control the solar heat gain (except for the EWI building). The working spaces were not well-served by daylight and the occupants had no or very limited control over their working environment. These strategies increased the dependency of conventional buildings on fossil fuels.

Generally, in sustainable buildings, a higher percentage of floor space was allocated to vertical shafts and communal spaces – such as atria, sky gardens and recessed balconies – so that the ratio of lettable to gross floor space was relatively lower in comparison with conventional buildings. In sustainable buildings, the central part of the plan was not occupied by a central service core; instead, multiple cores were placed along the perimeter of the building. Concerning plan configuration, a greater attention was paid to reduce the need for artificial lighting by placing permanent work stations close to the envelope and by reducing the plan depth. In order to reduce the cooling and heating loads, internal zones were separated according to the comfort requirements of office workers in two distinct areas with different temperatures. In this regard, a little bit of discomfort was acceptable at circulation and communal spaces, while a higher degree of comfort was expected at work stations. A post-occupancy study in tropical climates showed that the occupants of sustainable (bioclimatic) buildings such as the Mesiniaga and the UMNO building had a higher degree of satisfaction with the indoor environment compared to the occupants of conventional buildings (KOMTAR Tower). Climate-specific design strategies have been identified under four categories as follows:

Geometric factors: In sustainable buildings there was a greater tendency to utilise aerodynamic and curvilinear forms. The shape of the building and the use of envelope measures vary with a change in orientation. The orientation of the building was affected by the local climatic conditions (sun path and wind direction). For deep plan layouts, daylight was provided through a central atrium.

Envelope measures: In sustainable buildings, the transmission gains and losses through the envelope were considerably lower compared to conventional buildings. In temperate climates, a fully glazed double-skin façade with automated blinds (inside the cavity), operable windows and ventilated cavity were the most common strategies for the envelope design among sustainable buildings. In climates with higher solar radiation intensity (tropical and sub-tropical climates), recessed balconies, external shading, thermal buffer spaces on the hot sides, limited openings, and finally minimised surface-to-volume ratio were some of the strategies to control the heat gain and thereby to reduce the cooling demand.

Natural ventilation: Interestingly, eight out of nine sustainable buildings in the three climates used a combination of natural and mechanical ventilation, except the OFC building in a tropical climate. However, the duration and place of the use of natural ventilation varied depending on climatic conditions. In temperate climates, pre-heating the cool fresh air by solar gain (in the double-skin cavity) was found to be a necessity for natural ventilation to be further extended beyond the transitional seasons. The (central or peripheral) atria and sky gardens were an important part of the natural ventilation strategy. In temperate climates, the Commerzbank building might be the most successful example of implementing natural ventilation: some zones in the building use natural ventilation during the entire period of occupation annually. Introducing natural ventilation, however, might result in a slight increase of heating demand compared to a fully air-conditioned mode (see the energy results for the Mary Axe building in chapter 2) in temperate climates. However, the amount of energy that is conserved by using natural ventilation outweighed the increased heating demand. In temperate climates, summer night-time natural ventilation was a common strategy among sustainable buildings for reducing the cooling loads. In sub-tropical and tropical climates, the communal areas were naturally ventilated during a longer time than working areas. For this reason, the service areas were mainly located on the perimeter and occasionally isolated from the office spaces. Since the average wind speed is lower, specific design strategies were usually incorporated to increase the air flow speed.

Greenery systems: Among the 12 sustainable buildings, three of them used greenery systems (Commerzbank in the temperate climate, Mesiniaga and OFC in the tropical climate). Compared to other design strategies for tall buildings the impact of greenery systems on energy saving was found to be limited. In the case of the Mesiniaga tower, the result of energy simulations showed that the shading effect of plants, when integrated with balconies, was limited to around 0.4%, although the evaporative effect was not included in this study. Although the share of greenery systems for energy savings in high-rise buildings was found to be insignificant, other large-scale benefits for the urban environment (mitigation of CO_2 concentration) and building residents (increased productivity and higher well-being) could justify the application of greenery systems as an essential sustainability feature for the design of tall office buildings.

For better understanding the effect of architectural design strategies on the energy consumption of tall office buildings, an in-depth investigation was carried out accordingly. As a result, one chapter was dedicated to further investigate each category of architectural design strategies.

TOC

Question 3 (chapter 3)

To what extent do geometric factors affect the energy-efficiency of high-rise office buildings?

Performance-based simulations were carried out for 12 plan shapes, 7 plan depths, 4 building orientations and discrete values for the window-to-wall ratio (WWR) to quantify the impact of geometric factors on the energy efficiency of high-rise office buildings in three climates: temperate, sub-tropical and tropical. The base model was a 40-storey single-zone open-plan layout office with 1500 m^2 of office area per floor. For the purpose of simplification, the building's properties and operation details were kept constant for all building models in the three climates, except for two envelope measures. A sensitivity analysis showed that the building energy demand was highly responsive to changes in the glazing type and shading system. As a result, the appropriate type of glazing and shading system that suit each climate type best were selected.

A large number of energy simulations were performed using EnergyPlus, the underlying simulation engine for DesignBuilder. The results of the total annual energy consumption (and different energy end-uses) were used to define the optimal building geometry for each climate. Among selected options, the most and least efficient solutions were determined. The optimal design solution is the one that minimises, on an annual basis, the sum of the energy use for heating, cooling, electric lighting and fans. The percentile difference (a deviation in the total energy use) between the most and least efficient design options showed the extent to which geometric factors can affect the energy use of the building.

The results indicated that wrong decisions and design failures related to a building's general layout can increase the operational energy tremendously. In case of the plan shape, the highest to lowest deviation in the total energy use between the most and least efficient design options were observed for the sub-tropical (15.7%), temperate (12.8%) and tropical (11%) climates respectively. In a temperate climate special attention should be paid to plan depth, as the total energy use can increase more than in other climates. Furthermore, it was found that, among geometric factors, the building orientation has the highest influence on the energy use. A wrong decision, therefore, can increase the energy demand to a peak value of around 32% in sub-tropical climates. In all climates, a 0° rotation from the north was found to be the ideal orientation for energy efficiency. The investigation also highlighted the most sensitive orientations that potentially increase the total energy use (relative value) to a large extent for a wrong selection of WWR in different climates; those include the west-facing exposure in temperate climates (4.5%), the north-facing exposure in sub-tropical climates (11.3%), and the two facades facing east and west in tropical climates (up to 3.3%).

Question 4 (chapter 4)

To what extent do envelope design strategies affect the energy-efficiency of high-rise office buildings?

The impact of envelope design strategies for the energy-efficiency of high-rise buildings was investigated for two climates: the temperate (part a) and tropical climate (part b). For this purpose, an existing tall office building was selected as a typical high-rise design for each of the climates and the energy use prior and after refurbishment was compared through computer simulations with DesignBuilder version 3.4 and 4.7. The (21-storey) EWI building in Delft, the Netherlands, was selected as the representative for the temperate climate and the (65-storey) KOMTAR tower in George Town, Malaysia, for the tropical climate. Real building properties and real climate data were used as input for the simulation models. The DesignBuilder models of these buildings were validated by comparing measured and simulated annual and monthly energy use intensity (EUI) of the buildings for one year. As part of a sensitivity analysis, energy performance simulations defined façade parameters with higher impact on building energy consumption. A large number of computer simulations were run to evaluate the energy-saving potential of various envelope measures, as well as their combinations. The results showed which set of envelope measures suits each climate type best.

In the temperate climate, the total energy use of the EWI building was reduced from 354 kWh/m^2 to 203 kWh/m^2 when high-performance envelope measures were incorporated. This means a saving of around 42% for the total energy demand, 64% for heating energy, and 34% for electric lighting energy use can be achieved through selecting the right set of envelope strategies. The high-performance integrated design was comprised of a double-skin façade type with double-glazed clear glass for the inner pane and single-glazed clear glass for the outer pane, a WWR of 50% for the external leaf (and 60% for the internal leaf), and blinds (outside). While the glazing type had the greatest influence on the heating demand (if not including the influence of infiltration rate), shading strategies had the greatest influence on the cooling demand. In the tropical climate, the high-performance integrated design reduced the total energy use of the KOMTAR Tower from 320 kWh/m^2 to 205 kWh/m^2 (a reduction by 36%). The combination of envelope measures was comprised of external shading (overhang and louvers), spectrally selective glazing, a WWR of 80%, central service core, roof top shading with an aluminium coating, and air infiltration rate of 0.2 ac/h. Shading had the largest effect: it led to a reduction of the total energy use by around 25%.

Question 5 (chapter 5)

To what extent do natural ventilation strategies affect energy-efficiency of and thermal comfort in high-rise office buildings?

In chapter 5, the potential use of natural ventilation strategies to reduce the energy demand for cooling and mechanical ventilation in high-rise buildings was investigated by using the same validated base models from chapter 4. The investigation of natural ventilation strategies comprised of two main steps: (1) the study of the impact of natural ventilation strategies on indoor comfort indicators, including thermal comfort and fresh air during the operation of natural ventilation, by EnergyPlus; and (2) the study of the indoor air temperature and the velocity contours under different weather scenarios (during typical and extreme weather conditions), by Computational Fluid Dynamics (CFD). Different natural ventilation scenarios were developed for the base models in a temperate (part a) and a tropical climate (part b). In both cases, the reference buildings fully relied on fans and air-conditioning to provide comfort conditions at office spaces. The EWI building (temperate case) has a narrow plan layout with cellular offices, while the KOMTAR building (tropical case) has a deep open-plan layout. For the temperate climate, the investigation of natural ventilation strategies was limited to summer; for the tropical climate a full year study was performed. The precision and accuracy of CFD simulations were tested accordingly. More details on the methodology can be found in chapter 5.

Part a: In the temperate climate, natural ventilation strategies could provide thermal comfort and fresh air for up to 90% of the occupancy time in summer (May-Sep) and therefore can save energy that is generally needed for the operation of traditional mechanical ventilation and air-conditioning systems. Most of the ventilation strategies had almost the same performance except for that combined with a poorly ventilated double-skin façade which was less efficient. To put it another way, a buoyancy-driven ventilation strategy (e.g. using an atrium) had no significant advantage over a wind-induced ventilation strategy (e.g. cross ventilation) in terms of energy saving and thermal comfort for long narrow buildings in temperate climates.

Part b: It was found that for on average 96.8%-99.8% of the occupancy hours, natural ventilation strategies could meet the minimum fresh air requirements needed for an office space in tropical climates. However, an assistant mechanical ventilation system might be essential for up to 10% of the occupancy time on certain floors, depending on the physical mechanism driving the air flow. Furthermore, the results showed that the application of natural ventilation strategies can reduce the percentage of the time (during the office hours) considerably when air-conditioning is needed for space cooling in the reference building: 80%-88% for the wider comfort boundaries (80% acceptability limits) and 56%-65% when selecting the narrower comfort boundaries (90% acceptability limits). The cooling effect of elevated velocities, however, was not included. In a next step, CFD simulations were employed to investigate the potential use of ventilation alternatives to improve thermal comfort by using Szokolay's physiological cooling equation. With the application of natural ventilation (NV) strategies, the average percentage (on different floors under different weather scenarios) of comfort area (based on 90% acceptability limits) increased to 25% in NV#1 (cross ventilation), 39% in NV#2 (full-height atrium), and 33% in NV#3 (segmented atrium). The area of comfort can be extended further when adding the physiological cooling effect of elevated velocities. The results showed that the increased area of comfort due to elevated velocities were 53% in NV#1, 62% in NV#2, and 55% in NV#3.

Question 6 (chapter 6)

To what extent do greenery systems affect the energy-efficiency, thermal comfort and indoor air quality of high-rise office buildings?

The effects of greenery systems on the energy-efficiency, thermal comfort and indoor air quality of buildings were investigated by conducting a thorough literature review on five greenery concepts, including the green roof (GR), green wall (GW), green balcony (GB), sky garden (SG) and indoor sky garden (ISG). A literature review of the impact of greenery systems on thermal and energy performance of buildings demonstrated that investigations of this impact have so far been limited to low-rise buildings. Moreover, the few studies that are available also do not show a significant contribution of greenery systems for energy saving in high-rises. According to the literature review, outdoor greenery systems (such as green roofs, green walls and green balconies) can improve indoor thermal comfort through reducing heat fluxes and temperature fluctuations on the building envelope. While evapotranspiration and shading contribute to the reduction of the cooling load, the effect of greenery systems for reducing the heating load is a subject of debate. In places with many heating degree days, shading and evapotranspiration can lead to a slight increase of the heating load in winter, due to a small amount of evapotranspiration and because only old buildings with poor insulation properties can take advantage of the extra vegetation layer for insulation. The maximum efficiency of greenery systems was reported during summer and for places with higher solar radiation and when integrated into buildings that have no solar control systems. Furthermore, it was found that greenery systems have a limited impact for reducing the energy use of high-performance buildings. In both temperate and tropical climates, the results of energy simulations on the EWI and KOMTAR buildings (chapter 4) showed that adding a 10 cm green roof to a well-insulated roof has a negligible effect on energy consumption for cooling or heating, and that the total energy use is almost the same as a well-insulated roof without a layer of vegetation.

TOC

Indoor plants can provide indoor comfort through purification, humidification and temperature reduction. Indoor vegetation (indoor living walls and indoor sky gardens) contribute to the purification of indoor air through bio-filtration. In addition, through photosynthesis, plants take up carbon dioxide from air and release oxygen. It was found that one square meter of ivy plant can absorb around 2.3 kg of carbon dioxide from the air per year. As a result, they might reduce the need for ventilation; hence, contributing to energy savings. Furthermore, a few studies showed that there is a correlation between the usage of green spaces in tall office buildings and the comfort level of occupants. From a psychological point of view, plants can improve the users' satisfaction with the indoor environment by reducing stress and increasing health and well-being, hence improve the productivity of office workers.

Question 7 (chapter 7)

What are the essential architectural design features for high-rise office buildings' energy-efficiency in temperate and tropical climates?

The findings of previous chapters were used to point out general and climate-specific architectural design strategies that are required for energy-efficiency and sustainability of tall office buildings. It was found that compact shapes can improve the building performance more than slender shapes. Natural ventilation can play a key role in maintaining thermal comfort and providing fresh air for tall office buildings. Therefore, it should be an integral part of ventilation design in tall buildings. A ventilation strategy should be able to perform under different wind conditions and outdoor temperatures. In this regard, the findings showed that a natural ventilation strategy that employs the combined effect of wind and buoyancy forces together is more successful. Different architectural elements can be used to enhance the effectiveness of natural ventilation, including atrium, solar chimney, double skin facade, sky garden and venturi roof. Shading is a key environmental control strategy to maintain thermal comfort inside the building and to reduce the energy consumption, especially in buildings with a large window-to-wall ratio. The importance of reducing (undesired) external thermal loads on vertical surfaces is even higher for the high-rise typology as they are more exposed to solar radiation and the extent of internal gains are higher compared to the low-rise typology with an equivalent floor area. When the use of compact layouts is a key factor for energy saving, other elements such as atria, sky gardens and transparent partitions are needed to enhance natural light penetration. Daylight has a direct influence on well-being, productivity and the overall quality of the internal space of a building. In office buildings, the share of electric lighting among the different energy end-uses is huge. To reduce the amount of artificial lighting, permanent working stations should be located on the perimeter to get access to daylight or should have access to an atrium.

Finally, greenery systems can contribute to improving the indoor quality of the space in different ways and therefore are among the essential sustainability features for high-rise building design. The central part of the plan should be allocated to an atrium for bringing daylight deeper into the building and for distributing fresh air in a relatively more uniform manner throughout the entire plan.

In temperate climates, compact forms perform better in terms of energy use. Among compact shapes, an oval shape has the best performance. A zero-degree rotation from north was found to be the best orientation to reduce the heat gain in summer and utilise the passive heat gain in winter. In temperate climates, double-skin façades (DSFs) were a vital ingredient of the design of tall office buildings, due to the various advantages they offer for energy-saving and sustainability. In winter, they could act as solar collectors and thermal buffers. During the cooler periods, tempered air from DSFs could extend the period in which natural ventilation is effective, as compared to situations when fresh air is directly brought to the interior of offices (for example from a single-skin façade). Furthermore, there was no need to employ external shading elements when using a double-skin façade. In this regard, adjustable blinds could be placed within a DSF cavity. In temperate climates, passive heat gains and daylight penetration are highly desired for reducing the heating and electric lighting loads, so a high solar heat gain coefficient (SHGC) and light transmission value (LT) were required. In temperate climates, buildings with a DSF system could take advantage of a fully-glazed outer skin to maximise the access to daylight and views outside, without compromising the energy saving targets.

In tropical climates, three forms achieved the highest performance, i.e. the octagon, ellipse and circle. While the circle had the lowest cooling demand, the other two shapes performed better in terms of electric lighting. In tropical climates, outdoor air temperatures are close to the upper comfort temperature limits. An increase of air movement could enhance heat dissipation from the body surface in naturally ventilated spaces; hence, the upper comfort limit could be extended. According to the physiological cooling model of Szokolay, greater velocities could extend the upper comfort limit by up to 5.6 K. In tropical climates, a single-skin façade system performed better than a double-skin facade system. Moreover, the SHGC of the glazing should be kept as low as possible, while a high LT coefficient could help to reduce electric lighting demand. Spectrally-selective glazing (SHGC: 0.42, and LT: 0.68) was found as the optimal solution for high-rise office buildings in tropical climates (which need high light levels and have a long cooling season). It was found that north and south façades needed fixed horizontal shades (such as overhangs) to cover high sun angles, whereas east or west facades required adjustable shades or higher coverage of fixed louvers to block a wide range of sun angles. With the use of a high-performance shading strategy (using a combination of overhang and louvers with higher coverage on the east and west sides), the optimal WWR could be raised to 80% (or more if possible). It is important to note that a high WWR should only be recommended for buildings with effective solar heat transmission control strategies. Low sun angles in the morning and evening are a source of glare when daylighting is provided through east- and west-facing windows. As a result, high WWR values are not recommended, even if the building is featured by effective solar heat control systems.

§ 8.3 limitations and challenges

There are several points that need to be further discussed for the proper use of the findings and for the future development of this research. There are some limitations and uncertainties associated with energy simulation tools. Tall buildings can experience differences in atmospheric properties between the base floor and the top floor, in particular air temperature and wind speed. This might influence the comfort requirements (and energy demand) at different floors to some extent. EnergyPlus can extrapolate atmospheric variations from measured meteorological data at a given height; however, this function has not been incorporated in DesignBuilder interface version 5 yet (the most recent version of the program at the time of writing this thesis). Therefore, the impact of air temperature and wind speed variations at various altitudes could not be taken into account for the calculation of convective heat transfer, infiltration and ventilation. Although this is something important to be considered for the study of the comfort requirements at different floors of a tall building, the influence for the whole building energy simulations is expected to have less significance.

DesignBuilder is supplied with a database of wind pressure coefficients (C_p) from Liddament (1986), which is suited best for buildings of 3 storeys or less. However, for tall buildings (when the height is more than three times the crosswind width), it is recommended to override this default data. Ideally, the specific pressure coefficient data should be obtained from wind tunnel measurements using scale models of the building. However, wind tunnel testing is a very expensive and time-consuming method and therefore might not be applicable if the object that is being tested is too big. In chapter 5, the wind pressure coefficients used for the study of natural ventilation strategies were obtained from the experimental work of Davenport and Hui (1982). They determined the local pressure coefficients of a tall rectangular high-rise building located in urban terrain. As a result, the more relevant values of wind pressure coefficients were adjusted for different points on the façade. Furthermore, the discharge coefficient is a function of window characteristics (window angle and aspect ratio) and the flow direction. In this study, a default discharge coefficient (C_d) of 0.65 was used for windows and holes. The literature suggests that using a discharge coefficient between 0.60 and 0.65 should provide sufficient accuracy in preliminary design calculations.

There are inaccuracies involved with large horizontal openings and tall spaces for airflow network simulations using EnergyPlus. Although EnergyPlus allows to set up a dynamically varying temperature gradient to improve the accuracy of simulations in tall spaces such as an atrium, the air temperature distribution mechanism cannot be applied to the airflow network simulation. As a result, the effects of extracting relatively warmer air at the top of an atrium when using natural ventilation (scheduled and calculated) cannot be taken into account and the air would be extracted at the mean temperature. In this study, various geometries of atrium and different size of openings were tested in order to find the most reliable option. In this regard, the hourly temperature results and velocity contours were checked on different zones. The observations showed that the accuracy of the model's predictions was higher for an atrium model that is made from a single tall space (as opposed to an atrium model with a series of horizontal slices with multiple air flow connections between them) which is connected to the lower or upper levels by smaller horizontal openings. This is also the recommended approach for modelling tall spaces in DesignBuilder.

Validation is an important part of simulation studies, which can improve the reliability of the results. In this study, the DesignBuilder models of the EWI and KOMTAR building were validated by comparing measured and simulated annual and monthly energy use intensity (EUI) of the buildings for one year. For this purpose, the measured data were obtained from literature, in case of the KOMTAR tower, or from building management data, in case of the EWI building. Before the actual detailed simulations took place, sensitivity analyses were done first to address uncertainties related to the accuracy of the underlying models, input parameters, and building operation. The sensitivity tests undertaken also helped to have a better understanding of the relevant variables and their degree of influence on the building's energy consumption. For the study of natural ventilation strategies, different tests were performed to ensure the quality of CFD simulations. First, the results from the CFD simulations were used to inform the EnergyPlus model. In addition, the suitability of the grid definition and resolution for the generated models was tested through grid independency analyses. Furthermore, it was checked that hourly temperature results in various zones look believable for different ventilation scenarios that were investigated. Finally, the CFD simulation results were taken as valid solution only when residual Root Mean Square Error (RMSE) values had reduced to $1 \cdot 10^{-5}$ and when the selected dependent variable for the currently selected monitor cell reached a steady final value.

TOC

In DesignBuilder, two turbulence model options are available; k-ε, and constant effective viscosity. In this study, the most widely used and tested turbulence model, the k-ε turbulence model, was selected. The reason is because the constant effective viscosity model has a much simpler approach and it does not model the generation and transport of turbulence well. However, literature on natural ventilation shows that other turbulence models may be performing better in certain cases. As a result, when a simulation tool allows to choose among multiple turbulence models, the accuracy of the solution should be tested for different options to find the turbulence model that best predicts the actual situation.

The optimal design solution depends on the exact set of variables for the properties of the building and the operation details and the specific site location data. This study investigated the individual and combined effect of architectural design strategies for energy-efficiency of tall office buildings. In this regard, among other alternatives, the best design solutions have been identified for reducing operational energy consumption of high-rise office buildings. It is expected that, compared to conventional design, the recommended architectural design strategies could reduce the share of building design from energy consumption to a large extent; however, in order to achieve the maximum performance for each building, design optimisation methods should be employed according to the specific climatic conditions.

In chapter 4 for the validation of building energy models (comparison with measured data) and for the study of envelope design strategies, a single year weather data was used (the year 2013 for the EWI building and the year 2004 for the KOMTAR tower). Once the model is validated according to that specific year, it is better to avoid using single year weather data for the design optimization because one specific year could be exceptionally cold or warm. More comprehensive methods that attempt to produce a synthetic year to represent the climatic data within the period of record are more appropriate and will result in predicted energy consumption that are closer to the long-term average. In this regard, Typical Meteorological Year (TMY) and Weather Year for Energy Calculations (WYEC) more closely match the long-term average climatic conditions; hence, are better options for simulation-based building performance analysis.

When conducting simulation-based studies, there is always some degree of uncertainty involved with results considering the real effectiveness of design solutions after occupation. Therefore, it is important to include the interaction of occupants with the design during simulation (if possible). An example of such uncertainty is related to the control of operable windows for the investigation of natural ventilation strategies. In this study, natural ventilation was operated by automated windows. It means that natural ventilation was possible when the room temperature was within the predefined temperature set-points and when the offices are occupied. Therefore, the whole office used only one threshold to trigger opening and closing actions. To make the model appear like a real situation for window operation, future studies can introduce different set-points for opening and closing to include the occupant's interaction with windows.

§ 8.4 Lessons learned and future directions

As long as the issue of energy-efficiency is not properly addressed in architectural design, and the decisions regarding building design are substantially influenced by dated short-term visions (such as maximising the ratio of net leasable area to gross floor area), new tall buildings will remain in the group of intense energy consumer category of buildings. Energy-efficiency is essentially a matter of energy-wise decision-making during the design phase. Decision-making for a tall building design can have a long-lasting impact (positive or negative). Increasing the awareness and knowledge – regarding the consequence a decision might have on the performance of a tall building – can limit the number of ineffective designs. Given a broad discussion regarding the influence of architectural design strategies on building performance, this research aims to improve the awareness among different key players, and in particular architects, about the extent to which architectural design strategies can contribute to energy-efficiency of high-rises and improve the quality of the internal environment. The design recommendations defined in this study were based on a combination of theoretical guidelines, high-performance design references, international standards and simulation-based performance assessments. It is important to note that this research does not aim to prescribe one optimal form of design for tall buildings in temperate or tropical climates. However, the aim is to highlight the essential principles required for improving the performance of tall buildings without compromising the freedom to design.

This research set out certain boundary conditions. Expanding the research beyond these boundaries could help to broaden the knowledge about the high-rise typology. The focus of this study was initially on three climates (temperate, sub-tropical and tropical) where the majority of tall buildings have been constructed. In this regard, design strategies for cold and hot arid climates can be the subject of future investigation. Furthermore, the focus of this study was on one particular form of buildings, the high-rise office typology. In city centres and major transport nodes, mixed-use towers are becoming a substitute for single-use buildings, housing a combination of retail spaces, offices, residential apartments, hotel rooms, fitness

TOC

and lifestyle amenities, all in one place, as a mixed-use extrusion of the city. Mixed-use tall buildings offer great opportunities for the sustainable development of cities due to the concentration of different activities and the conservation of land sources. Therefore, more studies are required to understand the influence of design strategies on tall buildings of mixed-uses. There is no need to mention that different activities demand different comfort conditions. Moreover, the specific internal configuration of spaces in mixed-use buildings can limit the application of certain design strategies that is applicable in single-use tall buildings (e.g. the application of a central atrium to provide natural ventilation). As a result, to broaden the investigation of a mixed-use tall building typology is essential for the future development of high-rises. The influence of atmospheric variations on thermal comfort requirements and energy demand should be investigated, as it can result in buildings that need a different set of design elements or shape along the building height. Along with that, the most efficient option for the vertical arrangement of different activities should be defined. Future studies could also include the effect of neighbouring buildings in dense urban areas on the solar irradiation and wind flow patterns which in turn affect natural ventilation and shading.

A determinant contributor to the performance of buildings is the interaction of occupants with the implemented strategies, such as the control of windows or shading elements. Post-occupancy evaluations are of great importance in this regard. Feedback on main aspects of occupation, operation and performance of the building can be used to inform future design. Furthermore, the observation of case studies (chapter 2) showed that only in a few examples the actual performance data are given and compared to design predictions, which indicates that more public generation of data are required. This will give a good benchmark for the development of efficient tall buildings. Finally, the architectural design should not only provide energy efficiency, but most importantly should improve the quality of the internal environment.

§ 8.5 Conclusions of findings

In office buildings, the share of space cooling and mechanical ventilation from energy end-users are typically higher than other building usages. On the one hand, the occupancy density is high, so more energy is needed for ventilation. On the other hand, the large number of office equipment and people could increase the internal gains, so more cooling energy is usually needed to compensate the excessive internal gains. Natural ventilation strategies can reduce the need for cooling and mechanical ventilation to a large extent in both temperate and tropical climates (see Figure 8.1).

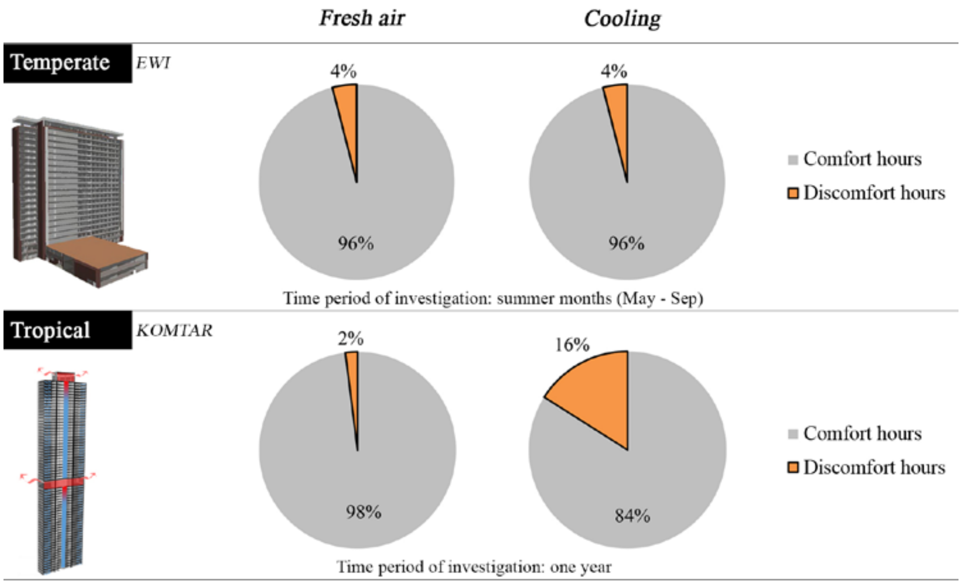

FIGURE 8.1 The percentage of the time (during the office hours) when natural ventilation can provide fresh air and thermal comfort (comfort hours) – based on 80% acceptability limits (a bandwidth around the comfort temperature of ±3 K) – compared to the percentage of time when air conditioning is needed (discomfort hours) in temperate and tropical climates.

For effective use of natural ventilation, it is important to use the right set of design elements that suit each climate best. In temperate climates, the outdoor temperature is typically below the comfort limit for most part of the year. The building design should provide this possibility to preheat fresh air before it enters the office spaces. DSFs and sky gardens are essential elements for naturally ventilated buildings in temperate climates. In tropical climates, the outdoor air temperate is very close to the higher comfort limit and the average wind speed is low. As a result, a high level of comfort is only possible during the rare periods of high wind speed. Providing the comfort conditions through pure natural ventilation might not be feasible throughout the year, although certain strategies can extend the time period in which natural ventilation is effective to provide indoor thermal comfort. The air flow across the interior spaces should be facilitated by using an aerodynamic building form, funnel-shaped spaces (for the offices and the sky gardens) and extended external walls (wind wing walls). Furthermore, the internal configuration of the plan should allow public and circulation zones to be naturally ventilated, separately from the occupied office spaces. Irrespective of the climate, the use of vertical shafts such as an atrium or a solar chimney could ensure effective natural ventilation, even on calm days with no winds. A venturi roof can be incorporated over the exhaust opening of a multi-story DSF, solar chimney or atrium to increase the flow speed and prevent the risk of down flows.

TEMPERATE		SUB-TROPICAL [1]		TROPICAL	
Design strategy	PD (%)	Design strategy	PD (%)	Design strategy	PD (%)
Geometric factors [2]					
Orientation	15.1%	Orientation	32%	Plan shape	11%
Plan shape	12.8%	Plan shape	15.7%	Plan depth	8.8%
Plan depth	12.4%	WWR (deep plan)	11.3%	WWR (narrow plan)	8.6%
WWR (narrow plan)	10.3%	WWR (narrow plan)	6.8%	Orientation	7.9%
WWR (deep plan)	4.5%	Plan depth	6%	WWR (deep plan)	3.3%
Envelope strategies [3]					
Glazing type	16.1%			Shading	25.3%
Shading	9%			Glazing type + WWR	14.6%
WWR (DSF)*	0.3%			Service core placement	2.4%
				Roof shading + reflective external walls	0.2%
Other influential parameters for the refurbishment					
Infiltration	29.3%			Infiltration	10%
External wall and roof insulation	2.3%			External wall and roof insulation	0.3%

PD (%) = Percentile difference. For each of the design strategies mentioned in Table 8.1, different alternatives were simulated and the variation was observed. The percentile difference in this table indicates a deviation in the total energy use between the most and least efficient alternatives. A large percentile difference points to a dominant effect of a design strategy on energy consumption.

1 In subtropical climates, the investigation was mainly limited to certain design strategies that had a greater impact on energy use, in particular geometric factors. For envelope strategies in sub-tropical climates, the parameters that should be addressed in the first place are similar to those presented for tropical climates.

2 The results of this section (geometric factors) were obtained from a building model that features a single-skin façade and indoor blinds for the purpose of glare control.

3 The results of this section were obtained from a building model that features a narrow plan layout, double-skin façade and blinds inside the cavity in the case of temperate climates, while for the case of tropical climates the building had a deep open plan layout, a single-skin façade and indoor blinds with low reflectivity slats. More information on the construction details of the investigated buildings can be found in chapter 4.

TABLE 8.1 The most and least important design strategies according to their degree of influence on energy consumption for each of the investigated climates.

Geometric factors – such as building shape, plan depth, transparency of the building enclosure and orientation of a building – are of great importance for minimising the energy loads and for enabling passive design strategies. Orienting the building to ensure maximum exposure to sun and wind energy is the most important step for energy efficiency. In addition, a building's energy consumption to a large extent depends on certain envelope design elements. For each climate/context, parameters with a higher impact should be identified – through a sensitivity analysis – and then addressed in the first place. Design measures of less significance can be decided afterwards. In a tropical climate, the solar radiation is the primary source of heat gain. In this regard, the shading and glazing type are the two most important mediums through which the extent of the admittance of sun radiation can be controlled and

TOC

therefore should be the first priority for any improvement related to the building envelope (see Table 8.1). The selection of the most efficient design option for the placement of service core and WWR should be decided afterwards, as their selection is highly dependent on the effectiveness of shading and glazing strategies. In a temperate climate, strategies that address façade type, window characteristics and shading systems should be the priority for design. In temperate climates, for refurbishment of an existing building, two other factors were found to have a determinant influence on the selection of envelope measures, including the air infiltration and insulation properties of external walls and roof. The effect of wall and roof insulation and of reflective materials for the external wall was found to be negligible in tropical climates.

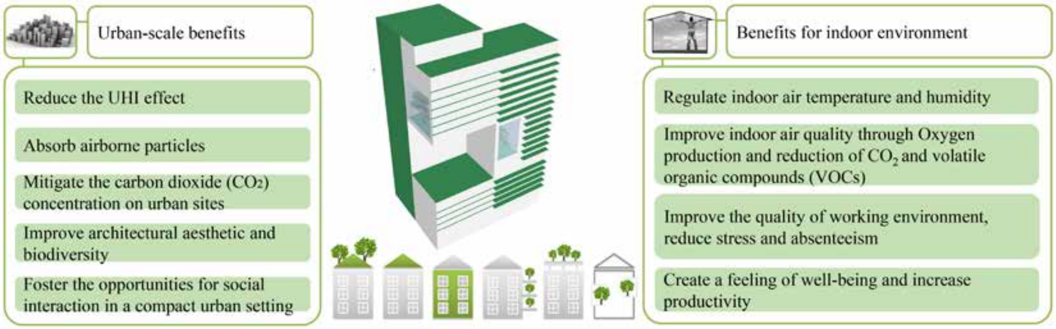

FIGURE 8.2 The contribution of greenery systems for improving the environmental quality of urban environment and the indoor working environment of tall office buildings.

With some design strategies (such as greenery systems), the energy impacts are insignificant, but the environmental value that such strategies offer could justify their application (see Figure 8.2). In high-rise office buildings, improving the environmental quality of design can result in a higher user satisfaction with the indoor environment so that the productivity of office workers increases. Every percent increase in productivity would have large economic benefits for the owners of commercial buildings. Architects can improve the environmental quality of design through creating areas that are thermally comfortable and visually appealing. Furthermore, designers should allocate a relatively larger portion of usable floor space to semi-open spaces such as atria and sky gardens. Apart from the contribution of such spaces to energy savings, they can create a sense of community up in the sky. To improve the usability and effectiveness of such spaces greenery systems can be integrated into design and these areas should be easily accessible and visible form working stations. Furthermore, occupants should be able to control their individual working environment (adjustable shading and opening). By addressing adequately this issues during the design, occupants would be more tolerant to high or low temperatures and would have a greater productivity.

§ 8.6 The future of high-rises

Although this was not part of this investigation, the future development of tall buildings presents an important question that still remains to be addressed. Are high-rise buildings actually a sustainable building type, compared to low-rise alternatives? The sustainability of tall buildings can be discussed from two viewpoints. As a single building, tall buildings have a greater energy expenditure, in both embodied construction and operation; hence they are less sustainable in their current form of design. From an urban planning point of view, tall buildings can contribute to creating more sustainable patterns of development through the concentration of land use in urban centres; hence minimising transportation distances. Furthermore, they provide a greater opportunity for renewable energy generation at height. So, it can be inferred that there is no one obvious answer to this question and different factors must be included to accurately quantify the overall sustainability of tall buildings compared to other typologies. Future studies might consider to calculate the floor count beyond which additional height would not make sense on sustainable grounds and this can be investigated in respect to different climates, cities and designs.

The real challenge for the future of high-rises is related to how well and how fast this typology can be integrated with the sustainable development trend. In this context, the future design should maximise tall buildings' connection with the city, climate and people. In order to contribute to sustainable densification, tall buildings should be comprised of diverse activities and well-integrated with urban planning. The combination of different activities also allows to reuse the waste energy from one function by another function to a greater extent. Along with energy-efficient and climate-adaptive design solutions, technological advances (such as smart materials and control systems) can be used as a great means to maximise the building performance and to boost the sustainability of high-rises. The exposure of the tall building to wind and solar radiation creates favourable conditions for on-site renewable energy generation. In this regard, the possibilities of clean energy generation should be a design goal. More liveable and vibrant design of internal spaces is essential for improving the quality of the indoor environment and the comfort of occupants. In this regard, future high-rises need more efficient use of greenery systems, daylight and natural ventilation. In office buildings, appealing views should be provided from work stations; besides, there should be a higher degree of flexibility for the use of spaces. Horizontal connectivity, social gathering spaces and civic functions should be provided up in the sky the same way they exist on the ground. In general, future high-rises should act like a smart vertical city. Will the future of cities depend on tall buildings? Only time will tell.

TOC

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Vancouver, July 2018

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